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Digital Fabrication, Rapid Prototyping, and the Development of a Costume

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Digital Fabrication, Rapid Prototyping, and the Development of a Costume

by

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Thesis

Presented to the Faculty of the Graduate School of

The University of Texas at Austin

in Partial Fulfillment

of the Requirements

for the Degree of

Master of Fine Arts

The University of Texas at Austin

May 2021

Dedication

To my parents, there are not enough words of thanks. My beginning and end, where I will always come back to, with all my love.

Acknowledgements

First, there were many people whose scholarship and expertise inspired the topic of this thesis: J.E. Johnson, Vanessa J. Lopez, and Nick Barnes. Jule Emerson and Marcia Provoncha: The mentors whose work guided me towards this industry. Jacqueline Heimel and Hallie Zieselman: for getting me to Texas. Caroline Reck, Marina DeYoe-Pedraza, and Khristián Mendez-Aguirre: for the gift of *Cucuy*. Bill Rios and Emma Craig: for always being willing to listen and problem-solve with me.

Finally, James Glavan, these three years of school have been a gift I will always cherish. Thank you for always expecting more, your endless enthusiasm, and shaping the artist I am today.

I would also like to thank my thesis committee for their tireless efforts combing through my words and for your insightful feedback and thoughts.

Abstract

Digital Fabrication, Rapid Prototyping, and the Development of a Costume

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The University of Texas at Austin, 2021

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This Graduate Thesis in Costume Technology is a case study investigating the workflows created by integrating digital fabrication into the costume development process. Collaborating with local puppet theater company, Glass Half Full Theater, I developed two pairs of fully articulated bird wings, one at half scale and one at full scale. The wings form and function were developed in collaboration with director/playwright Caroline Reck and performer Marina DeYoe-Pedraza.

Through this process, I investigated my hypothesis that a process of rapid prototyping and iteration, facilitated by digital fabrication techniques, could have dramatic and innovative impacts on how costumes are developed for theater, specifically in the world of costume crafts where fewer roadmaps are available to the costume technician.

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Introduction

My career in the arts began long before I entered the theater world. Since early childhood, I have been drawn to anything that involved creating - drawing, painting, sculpting, crafting, and beyond. I threw myself into whatever creative project I came across growing up, both in and out of school. By the time I got to college, I had every intention of continuing my education in the fine arts and pursuing it as a major.

What I had not planned on stumbling into was theater. When I started working on costumes for theater, I found a new outlet for my already well-entrenched artistic energy. Where before there was painting with paints and inks, there was now painting the look of all the characters on the canvas of the stage. Where there was sculpting, there was the creation of the garments that shaped the look of the figure. And embedded in every process I found creative problem-solving.

This was particularly true in costume crafts. The fabrication processes felt more like the already-familiar worlds of sculpture and painting and less like the sewing that I was only just beginning to master. I found my skills as an artist invaluable to navigating the more wacky and nontraditional costume pieces I was asked to work on, such as giant mouse heads, raptor claws, and banana costumes. The already-established processes I was used to in painting and sculpting, where I would do a lot of self-assessment throughout the process by stepping back to see how projects were progressing, served me well in these contexts.

Over time, however, I saw how the looser approach to costume crafts I employed was only just scratching the surface of what was possible in the world of costume fabrication. It also had its shortcomings. On several occasions, when I found myself dealing with a problem involving a costume piece, I found the process that had gotten me to that point suddenly let me down.

One such moment I remember in particular: I was constructing the famous donkey head for Bottom in Shakespeare's *A Midsummer Night's Dream*, and I had created a wire armature attached to a ski helmet. I thought I had cleverly avoided the need to make a custom base for the head by using the ski helmet and that it freed me to put my energy into the wire structure. I had made a different animal head on another project that used a bike helmet as a base, and we discovered it did not hug the head tightly enough causing a great deal of instability. The ski helmet was a much snugger fit, so I was confident in its effectiveness. I looped the wire through the holes in the helmet and began to flesh out the form before covering it in paper mâché. We did a fitting to make sure everything was working as we had hoped before proceeding to add the paper mâché and the fur. The performer tested out different movements with the head and was feeling comfortable in his movements. What I did not anticipate after the fitting was how the added weight from the paper mâché and fur would change the balance of the head. When the actor put it on a second time, the weight in the snout made holding his head up straight very uncomfortable. Suddenly the well-secured paper mâché head was a problem rather than a solution. The only option available was to separate the head from the helmet and move the head farther back so that its center of gravity was more in line with the actor's natural posture. Because of how I had attached the wires to the helmet and proceeded with the sculpt, this process was incredibly tedious. When I initially set out to do the adjustment, I was afraid it would be impossible without damage to the head. While things worked out in the end, I learned a valuable lesson in how the construction technique of a costume piece can have consequences for unforeseen circumstances down the road. If I had worked more adaptability into the fabrication process, I could have avoided the several frustrating hours spent wrestling the head off of the helmet enough to shift its placement.

Illustration 1: Zac Lounsbury as Bottom and Liana Barron as Titania in Middlebury College's production of A Midsummer Nights' Dream (2016). Photo by Stan Barouh.

Enter digital fabrication and rapid prototyping. I had already heard about and seen some projects that used it, and I was curious. This new technology seemed to have everyone familiar with it buzzing, and the implications for costuming felt exciting.

Inspired, I enrolled in a class on Digital Fabrication with The University of Texas at Austin professor, J.E. Johnson. To say this class was a revolution for me would be an understatement. Through this class, I was able to get a glimpse into the world of digital fabrication and the possibilities it created. We learned the basics of 3D printing and laser cutting and lightly touched on CNC milling. We also became acquainted with the 3D modeling program Fusion 360, which, while initially frustrating for someone like me, who had no experience with such software before the class, eventually was a source of amazement and inspiration. I was so in awe of this process, where a digital file I had created on the computer suddenly became a real physical object. And beyond even this initial revelation, I was further inspired by the implications of this process.

I had created a large monster head for the class using 3D modeling and an "unfolding" software called Pepakura, which turned my 3D file into a 2D image that was then cut and etched on the laser cutter and that would assemble into my model through strategic folding. For my first attempt to create the head, I chose a four-ply chipboard. I quickly realized that the chipboard was too thick, and that I would need the two-ply thickness. If I had made these pieces through more analog means, I would have just doomed myself to hours and hours of painstaking and tedious cutting of the 500 or so pieces the head contained. Instead, I had to wait about two hours for all of my pieces to be cut by the laser cutter. Time was wasted, certainly, but because the process was aided by digital workflows, the impact was exponentially less disastrous than had it been an analog project.

Illustration 2: The two versions of the Quetzalcoatl head, fabricated for Austin Maker Faire 2019. The successful cut on the left was made with an appropriately thin chipboard, while the first version on the right could not be fully assembled due to the chipboard thickness.

Around this time, I was reading the book *Prototyping for Designers* (McElroy), which detailed the ins and outs of developing products for manufacturing. While the book did not specifically focus on digital fabrication, it talked about the importance of rapid prototyping, iteration, and adaptation of ideas from initial concepts to final products. It was clear that this design process and digital fabrication went hand in hand. With the aid of digital fabrication tools, I could take an idea from beginning to end, modifying as I went, utilizing the inherently adaptive workflows that I had been introduced to in class. It was also clear that this exact mentality was already being explored in depth by makers worldwide. People from hobbyist inventors to start-up entrepreneurs to established engineers used digital fabrication to take their ideas from concept to reality.

The more I learned about the possibilities that digital fabrication offered, the more I saw a need for these workflows in costume technology. I thought that exploring ways to integrate the timesaving and inherently adaptive workflows of digital fabrication could revolutionize how certain costumes are developed. The field of costume crafts is only just starting to really integrate new digital technologies into its toolkit. I wanted to dive in and discover some of the possibilities out there.

Chapter 1: Costume Crafts

Costume crafts is a term that encompasses a wide variety of distinct skills including millinery and hat making, armor fabrication, jewelry making, shoe fabrication, dyeing —essentially any craft that is not dressmaking or suit tailoring. Craft artisans possess a broad range of skills in the aforementioned areas, and more generally in painting, sculpture, spatial reasoning, color theory, and traditional sewing techniques. Craft artisans possess such a wide range of skills because they are tasked with making one of a kind costume pieces that do not have the benefit of decades of tradition to guide them. While a dressmaker can refer to a library of books on draping and stitching techniques, a craftsperson might have to take one set of knowledge (say, hat making) and combine it with others (say, sculpture) to create something completely new like a wearable animal head or an oversized headpiece. This was true of my experience fabricating the donkey head for A Midsummer Nights' Dream and in costume crafts in general. I have a pool of knowledge that I can consistently pull from, but each project exposes me to more materials and making techniques. As with all learning processes, there were stumbles and occasional falls along the way. Sometimes these mishaps and discoveries were minor, and sometimes they set back a project by days.

It is the same for craftspeople who find themselves in the same situation of trying to deal with unforeseen problems. Not only do craftspeople often find themselves navigating new materials and processes because of the needs of a specific project, but there is also the capricious nature of theater itself. Directors change plans, actors make discoveries in rehearsal, money runs out, injuries put understudies on stage, and more. A testament to the ubiquity of this unpredictability is the popular Facebook group Costume People, which is populated by 7,000 members (and counting) of industry professionals and students of costuming. It is regularly a place to find people trying to troubleshoot unexpected costume problems. Scroll through the most recent posts in the group and you are guaranteed to see someone seeking advice on something that has broken, needs to be replaced or has been changed last minute. Shops develop their practices and techniques to mitigate risks from these common occurrences, but one cannot prepare for everything.

All of this to say, the typical costume craftsperson's' primary defense against the uncertainty of theater is to cultivate a broad set of skills in order to have as many tools at their disposal as possible. Experienced craftspeople are good at what they do not only because of their skill set but also because they have experienced and worked through a wide array of costume problems and found solutions. Indeed, Ingham and Covey assert in *The Costume Technician's Handbook* that while there are books and classes that can provide guidance in the area of costume crafts, "true expertise results from experience and experimentation" (399). For example, from my Bottom's head process, I learned dozens of small lessons in what to do and what not to do for a project like that. This system has worked for generations of craftspeople. They learn, make mistakes, carry that knowledge forward, and make more and more informed choices as they grow. One could even argue that the best craftspeople have simply made the most mistakes or lived through the most costume mishaps.

The two biggest challenges facing costume technicians are perhaps the two classic challenges of any project: time and money. The complaints are so often about a lack of either or both of these vital resources! In crafts specifically, these challenges usually manifest in a few specific ways. First, people will take shortcuts when possible, to save time. This can mean picking a fabrication process that doesn't create as durable an item as is ideal. Or, in the quest for durability, fabricating in a way that can lead to problems down the road (see my previous donkey head example). Second, to save money, people will use the materials on hand first. This also saves time as you aren't investing energy into resourcing and learning about a new material. However, this can lead to choosing the most convenient, but perhaps not ideal, material. Finally, under the pressure of time, craftspeople might not devote the resources to planning out the best workflow for a project. When every minute feels precious, pausing to think through the whole process might feel counterintuitive to working quickly. However, this can lead to time spent down the road backtracking or fixing mistakes.

This thesis revolves around whether there are better ways to work through the costume fabrication process than what is currently practiced, specifically involving new technologies. I hypothesize that digital fabrication and the workflows it facilitates can revolutionize the costume craft world as we know it. It can provide solutions to the problems of time and money. It can lead to higher-quality pieces that are as durable as they are attractive. And in freeing up time for the costume craftsperson, they can allow more time for developing, fine-tuning, and testing, ultimately leading to a better final result.

The knowledge base of costuming is either self-taught or spread by mentorship and guidance in the workplace. Like traditional dressmaking and tailoring processes over the centuries, experienced artists pass their trade on to apprentices and mentees, so that they may continue the tradition. The same can be said for costume crafts. While many craftspeople practice self-teaching, many start in assistant roles in costume shops and build their skills as they go. Most of the knowledge available out there is built on the foundation of the knowledge of previous generations of craftspeople, as they have discovered solutions to different costuming problems.

This means that the knowledge that most craftspeople draw from is inherently behind the curve of new technological developments. It takes time for new techniques to permeate the shops at the cutting edge of maker processes, let alone reach shops with fewer resources. And only once those shops have adopted those processes, even more time is needed to pass that information on to assistants. There is little research on the characteristics of costume shops across the country. Most of my knowledge of shops comes from my lived experiences, the experiences of other professionals I know, and what information is spread and highlighted in the industry. My interactions with other costumers have shown me that only a tiny percentage of costume shops in the country utilize digital fabrication to its full potential, if at all. Many of the shops that have access to these tools tend to be connected to prominent colleges and universities that can afford the equipment (such as UNC Chapel Hill, University of Kentucky, The University of Texas at Austin, and so on). Shops working at a large commercial scale are the other primary users of digital fabrication besides university shops. Santa Fe Opera, for example, is one of the largest and well-funded opera houses in the country. Yet, according to shop manager Kim Buetzow, they have only done "several productions" that relied heavily on digital printing, but all of that fabrication work was coordinated with shops in New York City. 3D printing and laser cutting have not entered into their process at all. Other theaters I reached out to, like the Old Globe in San Diego, the Guthrie in Minneapolis, the Oregon Shakespeare Festival, and the Seattle Repertory Theater, do not or only occasionally utilize these tools.

There are a handful of specialized costume companies that contract for Broadway, film, commercials, and other well-funded live performance venues, but still these are clustered in significant costume-making hubs like New York and Los Angeles. For example, companies like Gene Mignola (digital printing), Hat Rabbit Studios (3D printing among other services), Vogue Too (laser cutting among other services), and Mio Design NYC (custom fabrication using many digital fabrication tools) are all in the greater New York area. They are some of the handfuls of shops that contract out to larger and more distant shops like the Santa Fe Opera.

Vanessa J. Lopez, a recent graduate of the University of Texas at Austin, did a similar informal survey for her thesis on 3D printing in the costume industry. She came to the similar conclusion that digital fabrication, specifically 3D printing in the case of her thesis, was rarely utilized in costuming, often due to lack of resources like money for equipment and time to learn how to use it. Her thesis, like mine, started from the hypothesis that a huge opportunity is being missed in costuming (Lopez, 1).

This thesis and other projects like it can be looked at as an attempt to bridge the gap between the costume industry and the revolution of making being ushered in by digital fabrication. I want to help speed the adoption of new technologies and processes in theater. It is clear that the industry is only just starting to utilize technologies and that the innovation potential is too great to ignore.

Chapter 2: Digital Fabrication

What is Digital Fabrication?

Opendesk defines digital fabrication as “a type of manufacturing process where the machine used is controlled by a computer.” Three prominent examples of digital fabrication are 3D printing, laser cutting, and CNC milling. The advantage of digital fabrication is its ability to automate processes and allow for the more hands-off fabrication of products. Once programmed correctly, digital fabrication tools are reliable and consistent, and can create highly customized products. Digital fabrication not only encompasses the equipment that uses computers to fabricate objects, but it also includes the processes that these technologies facilitate. Perhaps even more impactful than the machines themselves are the opportunities in workflow and prototyping that they create.

All of the machines described below can be purchased at a variety of price points. As digital fabricating has developed, so have the tools. Mirroring past trends in other technological advancements, digital fabrication tools have become more advanced during the last several years while simultaneously becoming cheaper to purchase. Only the most high-end and advanced machines exist behind a price wall, while simpler versions can be bought for several hundred dollars. 3D printers, for example, are becoming so commonplace that they can be purchased at big box craft stores like JoAnn Fabrics.

Even if one can’t afford the cost of owning these pieces of equipment, maker spaces exist around the country (and the world) that can provide access. Makerspaces provide a valuable resource to those lacking space and resources who wish to work with fabrication machines under supervision and guidance from more experienced users.

Typically, makerspaces provide access for monthly fees, or hourly rates, providing options for various situations. These spaces often also facilitate educational workshops and can be great learning sources and provide equipment access.

There are also a variety of companies that can provide custom fabrication services. The precedent for such services is hardly new. Shutterstock and other photo printing sites made the previously multi-step task of getting film developed as easy as clicking a button. CustomInk has been turning people's ideas for custom T-shirts into reality for decades. Similarly, now we have sites that can provide similar services but for 3D printing, laser cutting, and CNC milling. These sites can create custom items based on visual information provided by the customer, taking digital files and using their own digital fabrication equipment to make them a reality. As the abilities of digital fabrication have grown over the years, so have the number of companies that can fabricate digital files. There are hundreds of companies that offer 3D printing, laser cutting, and CNC milling for different scales of production, in assorted materials, and on different timelines.

Companies like Treatstock, Scupteo, Shapeways and i.materialise allow you to upload 3D models to their websites and have them printed and shipped to your door. They offer other bonus services such as having experts check your model for optimization, allowing sellers to use their website as a storefront, and print material advising. These services are especially useful because they can easily print in such a wide variety of materials. All offer the classic selection of plastic printing, but in addition you have the options of metal, ceramic, resin, paper, gypsum, acrylic, foam, wax and even wood, depending on the company. On a much smaller scale, Etsy sellers are providing 3D printing services for individuals with their home printers. Similarly, 3D Hubs and makexyz LLC are printing services that connect you to individual printers and companies, somewhat like a matchmaking service. The benefit of their system is that you can connect to fabricators closer to your area and choose based on the specifications of your project. Large manufacturing companies like Materialise, 3D Systems, and Proto Labs offer an even more sophisticated range of options beyond simply printing small-batch items. They have the resources to provide services in areas such as biomedical, automotive, aerospace, semiconductor manufacturing and more. Many of the above companies also provide custom laser cutting services, injection molding, and CNC milling, which allows them to offer an even wider range of fabrication options to their clients.

3D Printing

3D printing is an additive manufacturing process where the printer uses materials ranging from plastic, resin, wax, ceramic, and more to essentially sculpt a product based on a set of computer directions known as G-Code. Printers catering to the individual maker (and their price point) can range in size from 5”x5”x5” to 15”x15”x15”, while larger printers catering to large-scale manufacturing can print objects several feet long and wide. These are printers capable of printing houses out of concrete or sand molds for casting metal objects. The current record-holder for largest 3D printed object is a twenty-five-foot-long boat created at the University of Maine (see 3D Natives). That scale is not accessible to the average user or even the average company, but you can see that almost anyone can find a printer at the right size and scale for them.

By far the most common type of 3D printer is the Fused Deposition Modeling printer (FDM), or Fused Filament Fabrication (FFF). These printers are so commonly available that you can purchase them at common craft supply stores like JoAnn Fabrics.

The printers work by extruding heated filament of some type of plastic in a thin stream one layer at a time. Mass is built up as the layers stack on top of each other. For most common FFF printers the extruder head moves side-to-side on an X-axis and raises and lowers on the Z-axis. The bed that the object prints on moves forward and back on the Y-axis, allowing the printer to move in all three dimensions and generate 3D objects. This style of 3D printing always produces prints with tiny ridges from the deposited layers of filament. The scale of these layers is determined by the user, with thicker layers common for prototyping and thinner layers used for more refined prints. For people planning to use the print as a final product, it is common to sand the prints after fabrication or coat them in special resins to fill in the layer ridges.

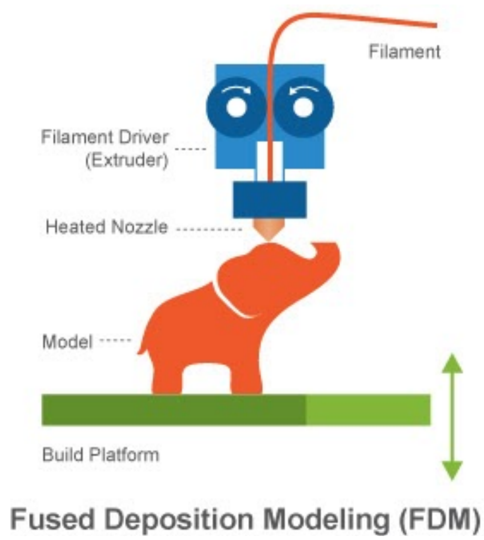


Illustration 3: Diagram of a Fused Deposition Modeling (FDM) printer. Image courtesy of Mark Jaster; https://www.printspace3d.com/3d-printing-processes/

There are also Stereolithography or SLA 3D printers. These are the oldest type of 3D printers. The SLA printer was developed and patented by Charles "Chuck" Hull in

1983 and presented in 1986 (McMills, 7). In this 3D printing method, the build plate is flipped upside-down compared to an FDM printer and lowered into a pool of photopolymer resin. When exposed to light, this liquid resin cures into a solid. Thus, the SLA printer "extrudes" by passing a UV laser over the build surface through the resin, curing it layer by layer as the plate rises out of the resin pool. The print must then go through a final cure after printing. First, the excess resin must be washed off with isopropyl alcohol. Then it is placed under a UV light to cure at which point it can be handled safely. This type of 3D printing produces an incredibly fine surface with almost indistinguishable ridges, but the washing process and resin bath can be messy if not handled with care. There are industrial-grade versions of SLA printing, such as Photopolymer Jetting, which has the benefit of being able to be handled immediately after printing. Another process is Continuous Liquid Interface Production that prints with no distinguishable layers and at incredible speeds 25-100 times faster than typical printing (Wheeler).

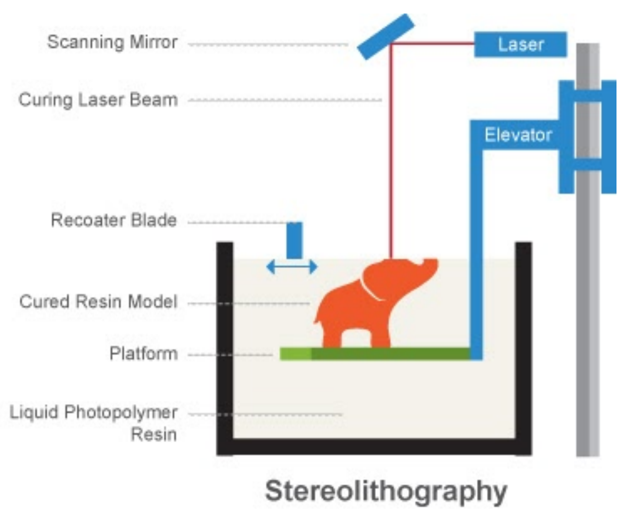


Illustration 4: Diagram of a Stereolithography printer. Image courtesy of Mark Jaster; https://www.printspace3d.com/3d-printing-processes/

Finally, there is Granular Materials Binding (GMB) printing. This process uses a reservoir of granular material, which can be anything from plastics to metals to glass to plaster and more. The material is deposited in a thin layer and then adhered. Layers build up in this manner: a layer of particles is bound together, granular material deposited, and then bound together again. When complete, the print is actually "buried" in the granular material that is deposited during printing but never adhered to the rendered object. The print is extracted, and the excess material can be reused for further printing. This process can occur through several different means. Powder Binder 3D printing deposits materials that are then bonded together with glue-like material. Selective Laser Sintering (SLS) printing uses the same process, except instead of a binding glue, the material is heated with a laser binding them together. The advantages of GMB prints are that they tend to be incredibly strong, and the variety of materials available to use is much broader than the other types of printers. Some machines can also print the color of the model as they build the object, creating shaped and rendered objects. This process is generally more expensive than the other two kinds of printing, as the machines are large, and the materials involved pricey. The machines themselves also tend to be much larger than FDM and Stereolithography printers, closer to the size of a refrigerator.

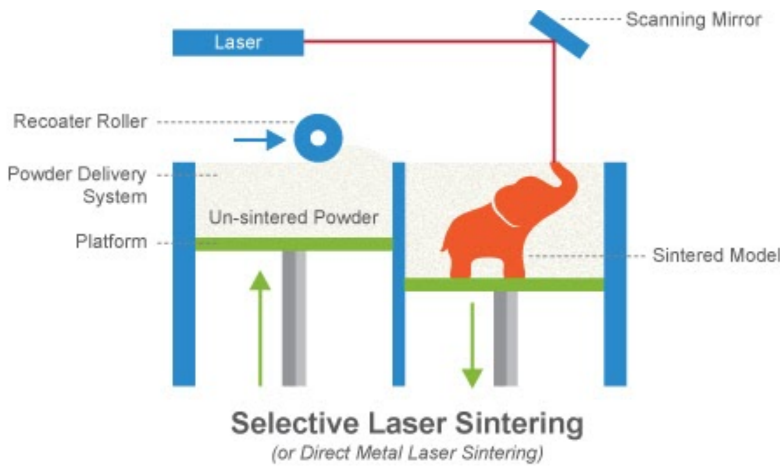


Illustration 5: Diagram of a Selective Laser Sintering (or SLS) printer, a type of Granular Materials Binding (GMB) printer. Image courtesy of Mark Jaster; https://www.printspace3d.com/3d-printing-processes/

Desktop 3D printing - the kind of 3D printing most accessible to the average maker not supported by a company or other funding entity - is ideal for smaller components in general. The size of the print areas for machines in the hobbyist price range is on average around 10”x10”x10”. SLS printers can generate larger objects (think around 20”x20”x20”). Still, their cost and size render them less useful to the casual maker. The user must determine which machine is best for their needs based on the types of product they wish to create, the space and tools they already have access to, and their budget. As mentioned above, makerspaces and online custom ordering can fill in needs when space and money are limited.

Laser Cutting

Laser cutting is a subtractive process where a beam of highly concentrated light is focused on a material. The heat cuts the material and exhaust fans blow smoke away from the cut area and evacuate the smoke from the cutter. They can also be used with various materials such as papers, plastics, and metals. The main restriction with laser cutting is whether the material being cut is dangerous to heat to high temperatures. PVC plastic, for example, releases poisonous vapors when cut with a laser that are caustic to the machine and potentially fatal for any humans nearby (Cleveland Public Library). Laser cutting is also not ideal for thicker materials, as they require many "passes" with the laser, and that much laser exposure can start to scorch your cut material. Laser cutters must be set up in a space that has exhaust vents installed. The fans that remove smoke from the machine need to be able to vent the fumes outside, otherwise smoke from the machine could fill a room to the detriment of the machine and the user.

Laser cutting happens in 2 dimensions. The machine can move the laser along an X and Y-axis. The Z-axis determines how the laser is focused, keeping the cut material the proper distance from the laser. The beam is directed straight downwards, and any dimension in the process comes from how thick the material being cut was from the start, rather than what it was carved or sculpted into (as with 3D printing and CNC milling). Another limiting factor of laser cutting is the size of the laser cutter bed. Laser cutters come in a variety of sizes, and the bed size determines how much surface area the laser cutter can cut at a time. The laser cutter I used for my thesis project, for example, has a cut area of roughly 24"x16." When cutting large quantities of material, you have to stay near the machine to enter cut commands and then extract and replace cutting material.

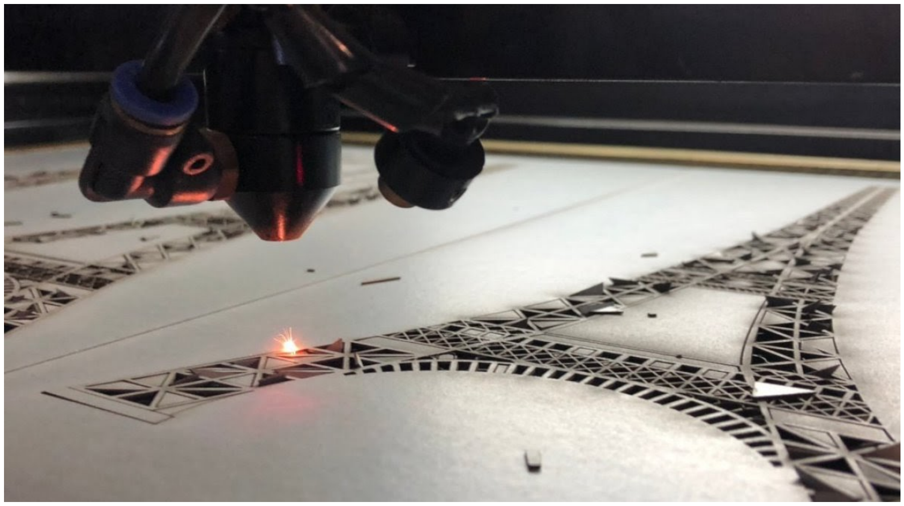


Illustration 6: A laser cutter slicing chipboard.

One strength laser cutting has that sets it apart from 3D printing and CNC milling is the polish of the finished product. 3D printing and CNC milling create forms with ridges on the surfaces because of the way their extrusion/cutting process works. Some higher-end models can reduce the visibility of the layers to less than 1/10th the width of a human hair, but you start to pay premium prices for that resolution. The average or casual user can expect to sand or coat the print after fabricating if a smooth finish is desired. Laser-cut edges are clean and typically require no extra labor to bring them to a finished state. Another strength of laser cutting is its relative speed. Depending on the complexity of the pieces being cut, using the laser cutter takes mere minutes. The 28 feathers I cut for my thesis project, for example, took 40 minutes to complete, with most of the time taken up by swapping out sheets of material to cut and re-loading the PDF into the program that communicated directions to the laser. The most complicated projects I have worked on have only taken a couple of hours, even the highly intricate cuts that have hundreds of vectors and require frequent re-loading of cut material.

The major downside of laser cutting is the price of the equipment. A typical laser cutter runs in the thousands of dollars rather than hundreds, and the smaller (and more affordable) machines tend only to engrave or cut small areas. They are also large pieces of equipment that take up significant space, making them logistically unrealistic to own for makers without workshops or available funds. However, they are fixtures of makerspaces just like 3D printers, and they are the sort of equipment that companies can invest in if requested. As mentioned above, many online cutting services can do the work for you with a vastly lower barrier to entry.

CNC MILLING

CNC milling is another subtractive process, but unlike laser cutting it can move on X, Y, and Z lines. In many ways, CNC milling is the mirror image of 3D printing. Instead of an extruder nozzle creating a form where there was none, the machine has a drill or grinding tip that cuts a material one pass at a time, working up to down. So, while a 3D printer is creating form, a CNC mill reveals a form from a solid material. Depending on the type of CNC mill, the machine will either move the drilling bit in relation to a stationary material, move the material in relation to the drilling bit, or move both in relation to each other, much in the same way an FDM 3D printer works.

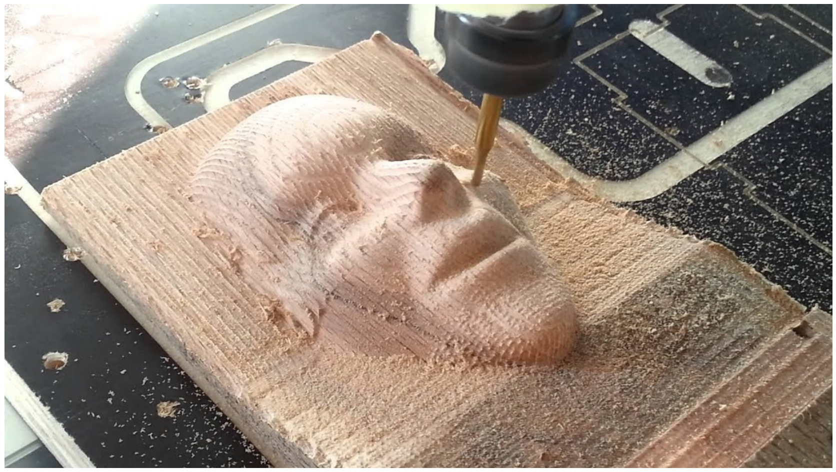


Illustration 7: A CNC mill carving a piece of wood. Image courtesy of Radu Sandovici.

CNC milling is useful because the workspace can be quite large and can cut very dense and sturdy materials in large pieces. It is widely used in construction - especially for custom cabinetry and countertops - because of its ability to cut precisely sized large sheets of materials to the specifications of a given room. A CNC mill can cut wood, metals, plastics, and other stable solid materials. It is also relatively fast, depending on the amount of detail and size of the cut. In that regard, they are comparable to laser cutters in speed.

A limitation of CNC milling is the material you are working with. Because you are starting from existing material, you are limited in thickness. If you want to carve a life-sized human bust, then you are creating something with a good deal of height. However, most available wood is not available in thicknesses greater than 3”. This means you have to preemptively slice your 3D model into 3” layers so that the CNC mill can cut it in sections. These sections then have to be assembled, either by bonding or with custom built-in joinery. Or you can select a material available in thicker sheets such as foam. The trick with cutting materials that thick however is finding a cutter of proper length and rigidity. If the cutter is not sufficiently rigid, then it will not be able to endure cutting deep into materials. A thicker and more rigid cutter means lower resolution. There are many variables at play and the user needs to carefully select the right combination of tools, materials, and settings for the job.

On the topic of cut resolution, another limitation of CNC milling is that most machines, like 3D printers, tend to leave ridges from the cutting bit. This is most apparent when cutting forms that have curved surfaces. Like 3D printing, this means that often items that have been CNC milled must be extensively sanded to bring them to a final polished state. You can mitigate ridges in your cuts by changing the cutting bits used to create a high-resolution finish.

CNC milling equipment is used mainly by manufacturing professionals. Because of the size of the machine and the mess they create, they are best suited to manufacturing shops with proper space, flooring, and ventilation. Some smaller models can fit into smaller workshops, but even the smaller models are around the size of a small office desk. The price can also be a problem. Consumer grade CNC mills start at least $3,000 and average closer to $15,000, a high barrier for the casual maker or smaller companies. Professional equipment commonly exceeds $100,000. However, because of the wide variety of materials they can cut and their ability to sculpt as well as slice, they can be valuable assets in fabrication of costume pieces. An exciting example is the fabrication of custom hat blocks carved from wood (Miller, 1).

SOFTWARES FOR DIGITAL FABRICATION

We have several examples of methods of manufacturing products digitally, but what happens before the equipment is turned on? How do we create the map that the computer is following to create the item? Every digitally fabricated product started just that way: digitally. Each piece of equipment has tried and tested best practices for creating the files with the information and the best software to create those files.

For 3D printing and CNC Milling, you need to generate a file that communicates three-dimensional information. Typically, this is an .STL file that one converts into G-Code. G-Code is a language that translates a 3D image into instructions for the machine to follow. These directions provide the coordinates on the X, Y, and Z axis that the machine moves to, and how movements happen. G-Code is typically generated by importing a 3D file into a program that generates G-Code. Some machines such as Prusas have conversion software built into the machine interface. Other machines that don't have this interface require you to convert G-Code through downloaded programs such as Cura, Simplify3D, and Slic3r on your computer, many of them for free. This code is then transferred to the machine for printing.

Before creating the G-Code, you need the 3D file. There are a variety of ways to acquire a model, depending on the situation and end goal. First, you can use open-source files from the web where models are shared freely. Sites like thingiverse.com have archives of different files that have been uploaded by users in the spirit of sharing assets. You can also capture existing forms using photogrammetry or 3D scanning, two processes that use photo or laser scanning of an object to turn real-world information into a 3D model (see below).

The bulk of my work for this thesis revolved around creating custom models tailored to my working situation. There are many types of software on the market that offer different workflows depending on the kind of shape you want. For example, Solidworks and Fusion 360 cater to people wanting to make mechanical parts or models with precise structures. Software like Maya and Mudbox give users a workflow more akin to sculpting a piece of clay and are great for making organic shapes. Each program offers different user interfaces catering to a variety of types of creator. For the execution of my thesis project, I worked in Fusion 360, so most of my case study revolves around that workflow. Fusion 360 is a great program for many reasons, but perhaps one of the most compelling is that I was able to download it for free as a student. Non-students can download a yearlong free trial of Fusion 360. Blender, Tinkercad, Meshmixer, and Sketchup are popular programs available for free.

For laser cutters, you need a file that communicates vector lines. This is critical because the machine will read an ordinary JPEG or similar image file type as a raster file. The laser will cut raster files in much the same way an inkjet printer works - moving back and forth, row by row. Raster files are helpful if you want to engrave an image into a material but not for efficient cutting. The laser cutter reads vector lines as paths for the laser to follow so that they cut along the line in one movement rather than in incremental passes. Typically, a PDF will successfully produce a vector image, but other file types can work. A good software for creating PDF files with vectors is Adobe Illustrator or VectorWorks.

It is also worth examining 3D scanning and photogrammetry in more detail. These two processes are different, but the results are the same: the user can turn a real-world object into a digital file that can be used for a variety of workflows.

Photogrammetry is a process where an object is photographed from various angles, and those images are read by a computer and turned into a digital 3D object. This process requires careful selection of object and environment when capturing an object.

Transparent materials, for example, will not capture well. The same is true for repetitive or symmetrical objects. There are ways to avoid capture issues, and I highly recommend Anne E. McMills' writing on it in her book *3D Printing Basics for Entertainment Design*.

3D scanning works by using lasers to scan an object, and a computer reads the information and turns it into a 3D model. There are two significant kinds of scanning: Laser Line Scanning (LLS) and Structured Light Scanning (SLS).

The advantage of these two tools is that if you already have an object on hand that is the shape you are looking for, turning it into a digital file is as simple as capturing its form. 3D scanning is a great way to replace damaged items with a scanned and printed copy, create multiples of a single object, or provide a starting point for further modeling.

OTHER TOOLS OF DIGITAL FABRICATION

The above-described digital fabrication tools are by no means an exhaustive list of what is available to the costume technician. Computerized fabric printing, engravers, embroidery machines, and vinyl cutters are just a few examples of what else is out there. Photogrammetry and 3D scanning, mentioned above, provide other workflows for creating 3D models. For this thesis, I will be focusing mainly on 3D printing and laser cutting, as that is what I used for fabricating and what tends to be the most accessible for the average costume technician. This is not to say that these other tools are less important or that they cannot impact how we develop costumes and costume accessories.

Maker Culture and the Maker Revolution

All of these tools and processes of digital fabrication have sparked what some have called the Maker Revolution or the Third Industrial Revolution (Anderson, 17). It encompasses digital fabrication tools along with the global information sharing facilitated by the world wide web. The tools of digital fabrication allow people's ideas to be realized without the need for startup costs or access to factories with manufacturing tools. The global web allows ideas and processes to be shared instantaneously without traditional barriers of distance and access.

Two major developments are converging to create the Maker Revolution: the Internet and digital fabrication technology. Obviously, the equipment is required for digital fabrication to be possible, but what about the Internet? The first answer is that wireless communication between machines allows many of these fabrication technologies to work more seamlessly - machines can communicate with each other without needing yards of cable. Software can be purchased and delivered without leaving your desk. That software can be updated with newer versions frequently and often automatically. One can transfer information and files created on one machine to another with ease. And finally, computing power can be done through servers rather than the user's computer (in my case, Fusion's computing is done on Autodesk servers), making the equipment needed to use the program more accessible.

But beyond the more obvious technical answers, something larger is at play with the rise and spread of the Internet. People are now able to share information not only with close contacts but the entire world. International boundaries and distance are meaningless when we can connect to the web. And this ability to share has fundamentally altered our culture: we are encouraged and even expected to share our experiences with others. Because people are sharing their experiences, others can find that information and contact them. Networks of individuals with similar interests form communities, and when they have a large enough community, start a movement. Such is the case now with Maker Culture and the Maker Revolution (Ibid, 21).

So, what is Maker Culture and the Maker Revolution? Maker Culture can be described by its emphasis on sharing of information, on its use of the web to connect makers, and how that sharing spurs further creativity and innovation. The Maker Revolution happening as a result of this culture is the period we find ourselves in - where technology is advancing at a breakneck speed and in a more democratic way because of the access that new technologies have given people worldwide (Ibid, 20).

I will delve into this in further detail later, but it is important to place the technology this study focuses on in the larger context of the culture that it is being made in. The power of digital fabrication and its tools are miraculous, but when you add to that the unprecedented ability to spread and share information that the Internet has given us, you can see how the strengths and potential of digital fabrication is amplified even more.

WORKFLOW

While workflow has already been referenced a few times already, I want to take a moment to talk more about it. Merriam-Webster defines workflow as “the sequence of steps involved in moving from the beginning to the end of a working process.” It is a very broad and versatile definition as evidenced by its use in a wide range of industries from consulting, to engineering, to web design, the arts and beyond.

In digital media, workflow tends to refer to not only the steps it takes to create a certain digital file, but also how that file then moves to other devices/equipment to perform tasks. For example, say your goal is to create a custom piece of jewelry for a costume. First, you have to design the look and structure of the jewelry, either in something as casual as a quick sketch or as formal as an orthographic projection - a schematic rendering of an object from multiple views with precise dimensions. Then, you have to go through the modeling process in the 3D modeling software of your choice. Next, that software produces a file for printing. That file then must be converted into G-Code for the printer. One must choose the proper settings for the printer, and then finally, the print is executed. You could call this series of steps a workflow.

Workflow is at the core of digital fabrication and the crux of this thesis. Finding the best workflow can revolutionize the way that projects develop. Building speed and adaptability into your workflow means that there is more time to iterate prototypes and fine-tune a product. Tools and material can impact the timeline of a project. Picking the best fabrication method can save time as well. These examples are moments where the nature of the workflow impacts your ability to meet your goals. I will cover a real-world example in more detail when I talk about the bird wing case study I performed.

RAPID PROTOTYPING

In her book *Prototyping for Designers,* Karen McElroy describes a prototype as "a manifestation of an idea into a format that communicates the idea to others or is tested with users, with the intention to improve the idea over time." Prototyping is the process of understanding a problem or problems. Prototyping helps makers communicate the idea they are developing to others, test the veracity of their ideas, and advocate for new ideas as they develop through the process (McElroy, 36). Rapid prototyping is a type of product development where that idea in development is refined after creating several versions of the desired object (or individual elements of an object) within a relatively short period. This workflow allows a maker to quickly create prototypes and test ideas without dragging out the process timeline.

Rapid prototyping is revolutionary for people trying to create something new with a user in mind. With rapid prototyping, they can quickly collect data from their desired audience and implement changes based on their feedback. The more rounds of data collected, the more confident one can be that the final version of a product will be well-suited for its desired use. The faster the prototypes are made, the more ideas can be tested.

Rapid prototyping is primarily used by companies both large and small looking to sell products. It is the latest evolution to the time-honored practice of doing consumer trials for products in development to make sure that people will buy said products.

This type of practice is less common in theater practice. First, as we have already established, costume shops underutilize digital fabricating equipment. They also tend to run on models that have been in place for decades. The typical workflow for the development of a costume once a design is established is to gather relevant measurements for your performer, create a mockup, fit the mockup to the performer’s body, assemble the garment in the final or “fashion fabrics,” and then a final fitting with the garment in fashion fabrics to determine if any final adjustments need to be made. Throughout the process there are conversations with the designer and performer about how the looks and feels on the body, and sometimes changes happen as a result of these conversations as well. Typically, after these fittings the next time the performer gets to practice with the garment is during dress rehearsals which can range from one to several weeks. Once this phase is reached, the timeline for alterations is extremely constrained and the typical assumption is that at that point only minor surface decorations or hem lengths are being altered.

That process is typically followed for more traditional costume pieces such as dresses, shirts, suits, skirts and so on. Nontraditional garments like masks, hats, added body parts, or that fall under the costume crafts category are under even more constraints for timeline and alteration because there is a less clear roadmap to solutions than traditional garment issues. Ingham and Covey describe the work of the craftsperson as “seldom repetitive,” creating “daily challenges” for the craftsperson to navigate (399). While there are many expectations and assumptions one can make when sewing a dress, for example, there are fewer available to the craftsperson. An experienced dressmaker knows how to build a dress so that it is easy to alter, knows what types of fabrics work well on stage for comfort and durability, and knows how clothes tend to move on the body. The same cannot always be said when making costumes that augment the body in extreme ways, or have specialized mechanics to them, or are made from nontraditional materials.

Imagine then what the development process could look like if it was easy and fast to create prototypes for complex costume items. Because they require little time to make and can be replicated easily, prototypes can be put into rehearsal while copies stay in the shop to allow for experimentation in the rehearsal room as well as the work room. If a part gets damaged or completely broken, it can be replaced with little impact on the costume shops’ daily schedule.

Chapter 3: Digital Fabrication and Costume Making

We find ourselves as costume technicians poised to take advantage of the tools of the Maker Movement. Everything from 3D printing, to laser cutting, to vinyl cutting is getting more accessible to the average user every day. Even if buying the equipment is out of your price range (or the price range of your organization), maker spaces around the country are more accessible than ever.

This isn't to say that digital fabrication tools are not already utilized in the greater field of costume making. While many theaters have not been able to integrate digital fabrication tools into their process yet, companies in the larger industry have adopted these practices. Unsurprisingly, some of the most exciting innovations are being explored by organizations with a lot of resources - film studios, international corporations, fashion houses, and large production companies. These include the variety of production studios that support the film industry, or companies like Cirque du Soleil, Walt Disney Studios, and more.

Companies like Cirque du Soleil, Ironhead Studios, and Legacy Studios all employ 3D scanning for fittings. This allows them access to the "bodies" of their performers without needing to coordinate fittings and potentially costly travel and coordination until much farther into the process (McMills, 261). Cirque du Soleil, for example, will create busts of its performers so that custom headpieces can be constructed for them. With an international troupe of performers and fabricators, this saves a great deal of hassle in moving people from one country to another. For the film studios, which deal with superstar performers whose time is costly, 3D scanning allows the costume makers to build and fit the actor and achieve a very reliable fit without taking up extra time with the performer.

One of the most common applications for processes like 3D printing and laser cutting is in the making of accessories such as jewelry, buckles, and other ornamentation. The costume shop at Oregon Shakespeare Festival, for example, used laser cutting to make butterfly decorations for a gown in Beauty and the Beast. The Guthrie has contracted out 3D printed items for their productions as well. The Santa Fe Opera has contracted out custom fabric printing. TV and film will frequently use 3D printing for accessories like buckles and decals. Netflix's *We Can Be Heroes* uses such accessories. The headdress worn by Queen Ramonda in *Black Panther* was 3D printed, as well as the heads for the characters in Laika's stop-motion animated productions including *Coraline*, *Paranorman*, and *Kubo and the Two Strings*.

Film production companies perhaps provide one of the most direct models that theaters can strive to emulate. Especially as equipment becomes more accessible, there are many workflows employed by these production companies that could serve the development process in theater. A typical process used by Legacy Studios, for example, is to prototype at half or quarter scale with pieces that can later be printed at full scale (Ibid, 265). Because they exist as a 3D model, the small prototypes can be easily scaled for prints at different sizes, resolutions, and material quality. Studios like Legacy Studios can afford printing with cutting-edge PolyJet machines that print both form and color. Still, it would not be unreasonable for smaller costume shops to scale costume pieces and skip the PolyJet coloring feature by doing surface finishes by traditional means. They would still save the effort of painstakingly scaling up a maquette and doing the work of sculpting an item all over again.

It is this last example that I find most striking. All of these applications are incredibly useful and certainly make a case for utilizing digital fabrication tools. Generating accessories and body doubles is undoubtedly important, but I think of them as using automation or digitization to replace analog workflows. The Legacy Studio model of using 3D modeling and printing to prototype and develop their objects is even more striking. Rather than finding another way to execute a task, they are using these tools to create new workflows and change the nature of the tasks themselves. In the same way that pre-visualization software can change the way architects design buildings, digital fabrication can change the way costume technicians develop and fabricate their costumes.

Chapter 4: The Case Study - Articulated Bird Wings for *Cucuy*

To put the ideas I had been researching for my thesis into practice; I set out to create a costume with digital fabrication as a core technique in the fabrication process. Initially, I was not certain what the best sort of project would be. I had been interested in creating costume pieces that altered or obscured the human body's natural movement. I was particularly interested in devices that made the human body move in a way that felt distinctly un-human. One of the areas in which digital fabrication can excel creating of elements that join together in specific ways. Digital fabrication is especially useful for puppetry or moving costume pieces, as the process of sourcing custom joints can be limiting and frustrating.

I had been inspired in the past by depictions of flight onstage and costumes involving bird wings. I am drawn to the complicated motion of the wings and the challenges they would pose as a construction and design project. I also found a wide range of costume wings, everywhere from film to stage to hobbyist's garage. Clearly, wings were a puzzle that many wanted to tackle, and given the wide range of what I saw, there was plenty of material to work with.

From this seed of a concept, the straightforward idea of "digitally fabricated bird wings," I would be led overseas for research, dive into the larger world of digital fabrication, and bring my wings to the center of the planning of a brand-new play.

THE CUCUY PROJECT

The project's focus arrived after being introduced to Caroline Reck of Glass Half Full Theater, based in Austin, Texas. As it happened, she was developing a play that had a character who was a magical bird/woman shapeshifter and is represented with various types of puppetry. The script was in development, and the actors had not yet started rehearsals. We agreed that my thesis and my idea to create manipulable bird wings fit the needs of their project perfectly. I was excited at the chance to research the mechanics of bird anatomy and for the wing prototypes to be tested by a professional puppeteer who could easily find any flaws in my designs. I was also excited about the developmental stage of the project. Because I wanted to see how digital fabrication techniques fared in the face of uncertainty or changes, the fact that so much of this project was undecided was an opportunity rather than a hindrance.

We began by discussing the themes at play in the script and who the character of Lechuza was. The play's description on Glass Half Full's website reads:

> Jesús Valles and Gricelda Silva play undocumented Latin American siblings living in Texas in the apartment of their older cousin (Lori Navarrete). In the midst of sweeping raids by the United States Immigration and Customs Enforcement (ICE) the older brother turns to the Latino tradition of telling terrifying stories to children (to make them behave) to train his little sister on tactics to avoid immigration agents. (Stay hidden. Don't speak. Don't resist.) Left alone, the siblings apply everything they know about escaping the boogeymen of their imaginations to avoid the very real threat of ICE agents who intend to tear their family apart.

In Latin American folklore, Lechuza is a spirit who, depending on the version of the story, is either a witch who can become an owl, a monster who is part owl and part woman, or a spirit who appears variably as an owl and a woman. In the play, Lechuza herself is an ancient and wise figure who comes and goes mysteriously and helps the young protagonist through her riddles and advice. Caroline and the performer playing Lechuza, Marina DeYoe-Pedraza, were interested in her design evoking age and bones, the earth, and wisdom. We also decided to use Spotted Owls as the primary owl inspiration for Lechuza’s design. Spotted Owls inhabit a territory range crossing the U.S.-Mexico border and are endangered by human activity. This felt fitting given the subject matter of the story where the natural world is disrupted by human activity, and the lives of humans are disrupted by man-made borders. The play honors the various forms Lechuza takes in folklore by having her also appear in multiple forms. She appears as both a true-to-size owl and as a full-sized woman who has owl features. That meant that we would need two sets of wings - a small set for Lechuza when appears as an owl, and a large set of wings for when she appears in a more human-like form.

Armed with this information and knowing that I would need two sets of wings, I continued my research into puppet mechanics and wing design. I also created initial renderings for how I imagined the Lechuza character would appear in the play:

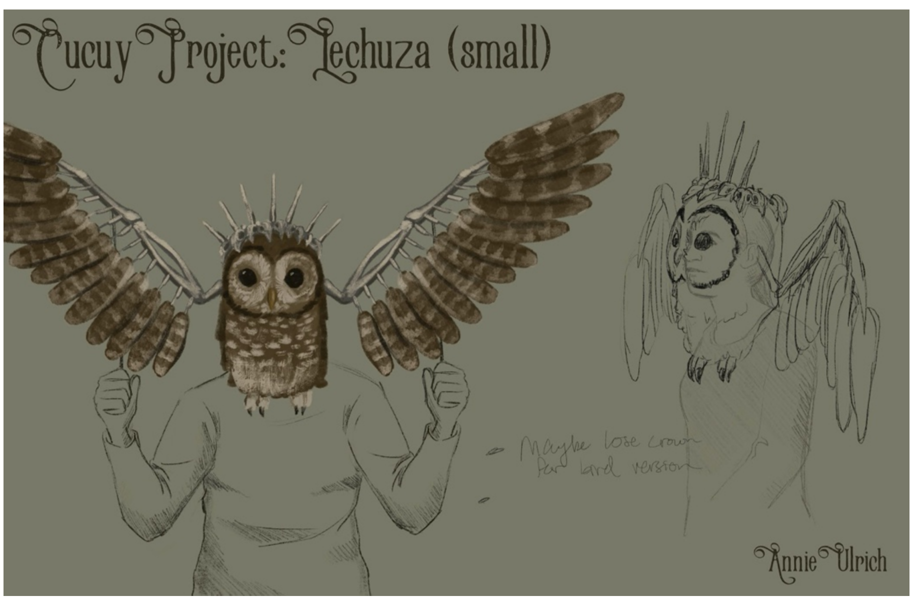


Illustration 11: Rendering of Lechuza with the small wing set.

Illustration 12: Rendering of Lechuza with the large wing set.

In our initial planning, we thought that Lechuza's wings would be operated by the wearer when she appears in her more diminutive form. The body would rest on the performer's head, and the wings would be operated by a rod controlled by each hand. For the large wings, the mechanisms would work the same way, and other performers would operate the wings much like the *Angels in America* wings. However, later on in the development process, it became clear that there would not be enough available hands during the show to make that plan possible. Instead, we decided that wings that were anchored directly on the puppeteer's arms would work better. This meant that I would have to see what elements I could translate from the half-scale wings to the larger wings while knowing that a great deal of adaptation would have to happen. It certainly meant more work than simply scaling up the wings, but it did provide another opportunity to explore the adaptability of digitally fabricated costume pieces. With the new information, I drew up a new rendering of the full-sized Lechuza:

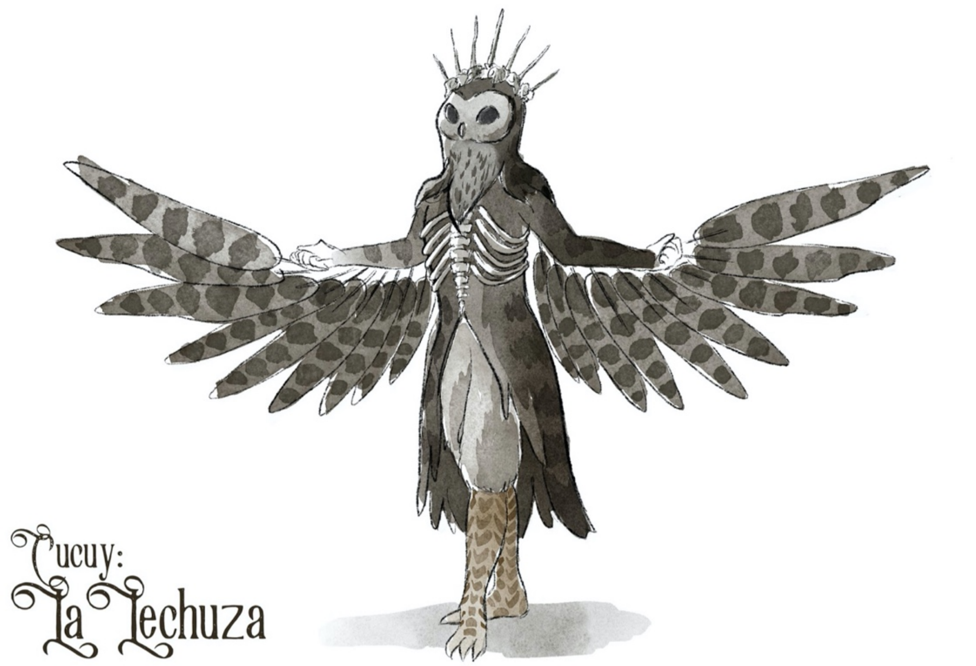


Illustration 13: Updated rendering of Lechuza, with the wing control now coming directly from the wearer's arms.

A note on the large wing set: due to timeline constraints and the scope of this document, the process for fabricating the large wings is not included in the chapters covering my build process. Most of the takeaways I had from that process only repeated and reinforced the lessons I took away from the process of fabricating the small wings and were thus omitted for clarity.

I felt prepared to move forward and dive into research for the project knowing the precise use of the wings.

Bird Wing Anatomy Research

Early on in the project, the goals were simple. I had to get a working understanding of bird wings, use principles of puppetry to mimic their mechanics, and then fabricate them. Since I was building a pair of bird wings, naturally, one of the first places I started was research into the anatomy of birds. I looked at bird skeletons, feather diagrams, and moving and static image captures of birds in flight to get a better understanding of how the wings moved during flight. One of my goals with this project was to evoke wing movement as realistically as possible, so understanding what qualities indicated realistic wing movement was crucial. I had seen various theatrical attempts to recreate wings on stage and wanted to improve on what I had seen as problems: that the wings movement did not feel real and that the wings could not fold up close to the body like real wings.

I started with skeletal research. Much like real bird wings, the puppet wings were going to function and move based on the qualities of the structure they constructed upon. I suspected that I could mimic the structure of real bird wings using either a human arm as a base or a structure designed to be manipulated independently from the body. At first, understanding the physical wing mechanics of when a bird flaps its wings was difficult. As humans, we tend to know how our own bodies move and function and have trouble understanding a movement that is different from ours. The hind legs of quadrupeds - four-legged animals such as dogs, horses, and deer - are a good example. Side-by-side examinations of human and quadruped leg bones reveal that compared to a human, quadrupeds walk on their “toes”. What we as humans perceive as a knee is an ankle, skeletally speaking. That is why their “knees” seem to bend backward. Similarly, when comparing the wing/arm bones of a bird to a human, you realize what you might think of as the “forearm” is the “fingers.” The diagram below shows the corresponding bones in humans vs birds. Notice how all the joints and bones present in a human arm are present in bird wings, just with different size ratios. From this research I would eventually conclude that what I was looking for in my wings was three bone segments: a humerus, a combined radius and ulna segment, and one large phalange that would represent the wrists and fingers, or specifically the carpals, metacarpals, and phalanges.

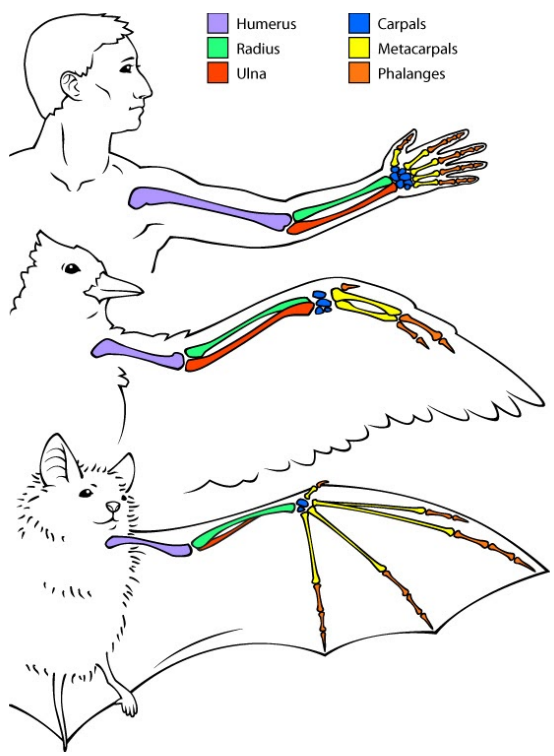


Illustration 14: Anatomical diagram illustrating the related yet different bone arrangements in the human arm vs bird and bat arms. Image courtesy of Elizabeth Hagan and Arizona State University.

The next area of research was the feather structure of wings. Bird feathers are incredibly complex body parts. They have sturdy but brittle and hollow shafts or rachis that support a network of hundreds of vanes covered in barbs that are in turn covered in smaller barbules that are then covered in little hooklets. These tiers of hooked offshoots allow the vanes to stay hooked together into a sturdy layer, a crucial quality for making flight possible.

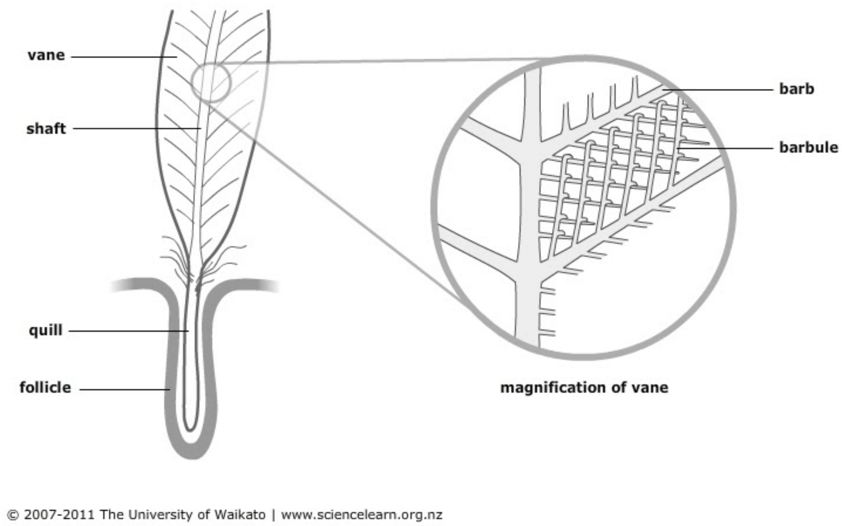


Illustration 15: Anatomical diagram of the anatomy of an individual feather. Image courtesy of The University of Waikato.

From a broader perspective, bird feathers come in various shapes, sizes, and textures, all specially designed to suit the needs of whatever body part they are on. In the case of the wings, you have several groups of feathers. The primary and secondary wings are what we tend to picture when we think of bird wings, as they define the "outline" or silhouette of the wings. They are the primary vehicles to flight for birds. The primary and marginal coverts are the feathers that overlap and cover the tops of the primary and secondary feathers. These define the "tops" of the wings. Abulas are a small group of feathers that sit right at the “wrist” of the wing and are critical for a bird’s ability to control its movement during flight.

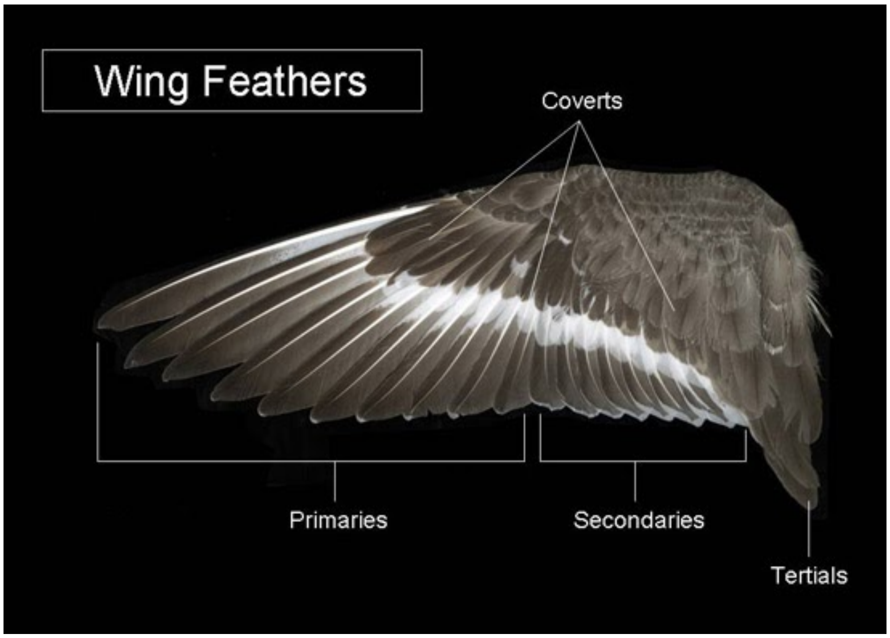


Illustration 16: A labeled photograph of a bird wing indicating the feather groupings. Image courtesy of the U.S. Fish and Wildlife Service.

I compared all of these anatomical qualities to existing bird wings that I had seen used on stage and in costumes. In terms of the skeletal structure, I noticed that the “humerus” bone was often left out in terms of skeletal structure, meaning the wings only had two segments rather than three. While this makes operation more manageable, it doesn’t allow the wings to fold up in a way that looks natural.

When I did see wings that had a realistic look to them, they were often fixed wings. Non-articulated wings allow the fabricator to meticulously assemble the feathers without the need to worry about movement. The Victoria's Secret shows are a great place to see beautiful static wings that evoke the feel and movement of real wings without actually moving.

Illustration 17: Victoria's Secret wings being fit and photographed on model Candice Swanepoel. Image courtesy of Huffington Post. Wings fabricated by Marian Jean Hose LLC.

I saw fully articulated wings being made by Alexis Noriega of The Crooked Feather, a cosplay wing company that specializes in pneumatic wings. The wings open and close with a remote trigger and Arduino microcontroller, and are mounted on a small backpack-type unit that anchors the wings and houses the wiring for the movement. I appreciated that her wings could open and close with joints that properly mimicked those of real birds, but I found them rather visually heavy. To hide the metal bones that the feathers attach to, she created a sleeve of real turkey feathers on a fabric base, mimicking the line of the covert feathers. The sleeve has to be able to move with the wings, and because the feathers are moving around all the time, they have a fluffy appearance. This was my main issue with this wing design - I wanted wings that had a lighter look to them, capturing the power and the delicacy of them, as well as their sleek lines.

Illustration 18: Wings fabricated by Alex Noriega of The Crooked Feather. Image courtesy of The Crooked Feather

My favorite pair of wings that I came across was in the National Theater production of *Angels in America* (2015). The famous angel character in the play sported a pair of eight-foot-long wings that moved independently from her, thanks to a team of puppeteers/dancers. These performers operated the wings, moved around the Angel and the stage as shadowy characters, and at various points in the play lifted the Angel into the air while flapping her wings, creating an instant illusion of flight. While the wings lacked many qualities of real bird wings, like a humerus bone, layers of feathers, or even the clean lines of real feathers - I still accepted them as alive. I believe this was thanks in large part to the flexibility of the movements of the wings, which allowed the performers to capture the gestures of flight. The way the wings flapped, folded, twisted, and emoted gave them a life that made the viewer wholly invested in them.

Illustration 19: The Angel in the 2015 production of the National Theater's *Angels in America*. Photo courtesy of Helen Maybanks.

This drove home the point that the key for my wings was going to be movement and preserving the essence of wings without sacrificing their ability to open, close, flap, fold, and pivot. What I needed were wings that worked like puppets.

PRINCIPLES OF PUPPETRY

I had already taken a puppet fabrication class at The University of Texas at Austin. We made marionettes and hand-and-rod-style puppets (such as the foam puppets typical of children's TV shows). I had also taken a hat-making class and had experience with making costume pieces that rested on the performer's head - as the owl body would be for the small Lechuza. From these experiences and lessons, a few foundational principles stood out.

First, weight is everything. Puppeteers can be exposed to injury if the weight of the puppet they are operating is too heavy. Ideally, the puppet should add as little extra resistance to normal movement as possible. While it seems like a simple goal - to create the lightest puppet possible, the weight principle is constantly in dialogue with its cousin - strength. The puppet fabricator is always searching for incredibly lightweight materials that are durable and sturdy. It is a judgement call of where to invest ounces in the name of strength, and sometimes one must be sacrificed for the other.

The next principle is ergonomics. The puppet's mechanisms for manipulation must not strain the puppeteer too much. Ergonomics is a trickier principle to adopt than one might think. There are many movements that might seem to be easy and comfortable to perform for extended periods of time. However, repetition and fatigue can make many seemingly safe and ordinary movements difficult over time. Part of this is related to weight - the more strength one exerts to operate a puppet, the sooner fatigue sets in. It is also related to how natural the movement is for the human body and which muscles absorb the strain of operation. For example, puppets that utilize the arm's biceps in an upward-pulling motion present little strain for the puppeteer, as this is a natural movement and a relatively strong muscle on the human body. In contrast, a puppet that requires the puppeteer to extend their arms out for a long period of time will cause strain, as the deltoids of the upper arm tire quickly in such a position.

Finally, we learned a great deal about puppets and their joints. Depending on the amount of movement desired, you need joints that are durable, able to handle the strain of being used, and resistant to torquing or misuse. With marionettes, for example, the key to the joints is constraining them so that they only bend in the proper directions. Because they are operated by pulling on strings, you have less control as a puppeteer over how the joint moves. Therefore, you must make certain movements “off limits” preventing the rubbery joint effect that can happen with under-constrained joints. With bunraku puppets, a style of puppet where the manipulation occurs directly on the puppet body, so constraining the joints is less important than creating a flexible and durable body, because the movement constraint comes from the puppeteer.

Keeping all of this in mind, I knew that I had to solve several joint problems. The first joint was the “shoulder” joint or the joint that attaches the wings to the body. This joint needed to work like a ball-and-socket - able to rotate and move laterally on all of those axes of rotation. Next was the “elbow” joint. This joint had to hinge like a standard elbow, but it also had to have the ability to yield to force in directions off of its normal range of motion. The “wrist” joint had the same needs as the elbow joint. Finally, there was the yet-to-be-determined joint that would control the movement of the feathers. With real birds, individual feathers are controlled by a network of tiny muscles and nerves that allow the bird to fine-tune feather orientation during flight. This level of detail would not be possible or helpful in the context of a puppet wing, so instead I focused on the basics of what was needed: each feather would be suspended from and perpendicular to the bone and freely pivot on an axis following the length of the bone.

The next area of research was about the feathers themselves. The micro-anatomy and physics that allow real bird wings to function were beyond anything I was capable of for a project of this scale. However, I could still use the basic principles of how feathers work to inspire mine. Specifically, I zeroed in on the shaft or spine that serves as the main support for the feather. In my design, the shaft could be the means of connecting the feathers to the bones in some yet-to-be determined way. They would need to be made with something stiff but lightweight. The general shape that the vanes form around the shaft could be created with a lightweight and flexible material.

RESEARCH ON EXISTING COSTUME WINGS

One of the first places I looked for information on material, mechanics, and joint design was Alex Noriega's website and posts about making her pneumatic wings. While I was not interested in the pneumatic movement controls, I was curious about materials and the process for the making wings themselves. Noriega runs a Patreon account where for $2 a month, you can have access to process videos, materials lists, and other information on her process. The paywall was low enough that it felt worth investing in access to that research material. Some of the most helpful information I took away was how she strung her feathers with a guide string that controls the spacing of the feathers as they open and close. The string lets the feathers collapse and overlap each other but then keeps them from spreading too far apart when the wings open. This trick is common to most mechanical wings you'll find if you search for mechanical wings. It is a simple way to add constraint to the feathers without needing to have that role served by the pivot points for the feathers. It also helps ensure the feathers overlap in the proper way every time they open and close. Another process described on Noriega's Patreon is the custom-made large feathers and their components. The feather base is EVA foam, clad in a cotton broadcloth. She has a specific process of applying Loctite glue to the fabric and the foam and pressing them together with a wire in between. This technique allows for a better grip on the wire and gives the feathers a better painting surface.

I had looked extensively at the wings that were created for the 2015 National Theater production of *Angels in America*, co-created by Nick Barnes and Clint Wingrove. I looked at behind-the-scenes footage of the performers working with the wings and interviews with Nick Barnes about his process and his studio in Hove, England. From these videos, I could glean specific details about how the wings worked, like the control of the wings and how the pieces fit together to make educated guesses about the materials. However, there was plenty that was still hard to decipher from the materials I had access to. I decided to reach out to Nick Barnes to hear his thoughts on puppetry and wing making in general. I was fortunate enough to get to do a phone interview with him over the summer of 2019, where we discussed everything from materials, process, and philosophy of puppetry. Nick was generous with his time and knowledge, and I came away from the conversation inspired. He was quick to make the point that the key with puppets is how they interact with the performer. As tempting as it may be to constrain the movement of the puppet so that it can only move a certain way, you take away the puppeteers' ability to explore and discover movements that the fabricator might not have thought possible. The goal of the fabricator must be to give the puppet enough constraint so that it is possible to control it, but not so much that you limit the performer. Our conversation was so informative that I asked him about his studio and the possibility of visiting. He generously said that I was welcome to come for a tour, and I very soon after made arrangements for the trip. Once there, he showed us the puppets and puppet prototypes that were in the shop. It was a huge revelation to see so many types of puppets in person and close enough to examine their construction. There were several puppets that had bungee cords as the joints, including, it turned out, the wings from *Angels in America*.

Illustration 20: Prototype lion puppet with bungee joints photographed in Nick Barnes' studio.

I could not believe that the cord was strong enough to hold up to the weight of such large wings, but Barnes explained that they used an incredibly thick cord with custom-adhered caps that kept the wings in place. In those setups, the bungee will eventually fray and degrade over time, but replacement is so simple that it is worth it for what you gain in flexibility. The cord allowed the joint to rotate around the bungee with a simple pivoting motion, but it also let the joint bend in many directions. This solution was a perfect example of what he meant by creating movement for the puppet that was not overly constrained.

Illustration 21: Meeting Nick Barnes in his England studio, 2019.

Illustration 22: The pivoting elbow joint constructed with bungee cord and secured with custom caps. Photo taken in Nick Barnes' studio.

The shoulder joints that anchored on the angel's back also used the same cord. I had imagined some industrial-strength ball and socket joint was how the wings were able to move and pivot so well. The reality was so much simpler: they created a housing for a climbing-grade special carabiner clip called a KongFrog that clipped on and off of a ¾" thick loop of bungee cord embedded in a fiberglass corset worn on the body. This allowed the wings to clip on and off with little effort and meant that the wings could move at the shoulder in almost every dimension, which helped make their movement so magical on stage.

Illustration 23: The clipping shoulder joint created with a KongFrog and custom housing. Photo taken in Nick Barnes' studio.

If anything, the theme of the visit was "keep it simple!" Barnes described many processes where they set out to design and re-design complicated joinery, only to find themselves returning to using tricks like bungee cord joints again and again. He also said something that I found striking about the development of a puppet. To him, design and fabrication were complementary processes. The design is in the making and visa-versa. When you hit a roadblock in the making of a puppet, you can use design to find a solution, and when you understand the mechanics of what you are making, it informs your design. As someone with a background in both design and technical practices, it felt like a connection I had always sensed had been made concrete. The process suddenly felt as much about design as it did about technical problem-solving. And seeing how beautiful and seemingly complicated things could be made from very simple components freed me from the expectation that the only way the wings would work was with complicated specialized mechanics.

Illustration 24: Macaw puppet photographed in Nick Barnes' studio.

I also gained insight into puppet wings from performer and puppet fabricator James Ortiz, who came as a guest artist to The University of Texas at Austin in 2019. As a puppet fabricator, he had worked with puppet wings in the past, and when I asked him about his process, he said that the thing to understand with puppet wings is that "stylization is your friend." What he meant, to paraphrase, is that wings have so many complicated elements that you can lose the magic of the wings while trying to replicate everything. The key is making them move in a way that looks right and is easy for the puppeteer to work with.

After looking through dozens of images of bird anatomy, studying the work of expert makers, and clarifying what my goals were, I finally felt I had taken in enough background information to start my wing process. I was excited to begin to implement the processes and use the tools that I had been researching to see where and to what extent they were most effective.

Chapter 5: Making the Half-Scale Wings

The First Prototype

I began with the half-scale wings that would be used for the owl-sized version of Lechuza. In both traditional and nontraditional costumes and product development, it is common to start with a smaller version of your final item. This strategy allows you to work faster and consume fewer resources while doing so. The fact that I needed both a large and small set of wings simply formalized the scenario and meant that my smaller wings would be produced to a polished final state.

First, I had to create a proof-of-concept. My research into wing mechanics and existing wings for performance had given me a pretty solid understanding of where I needed to begin. Using simple rectangles of cardboard and brad fasteners, I made the base for the wings, and with wire I had on hand and string, I created the general arrangement of the feathers.

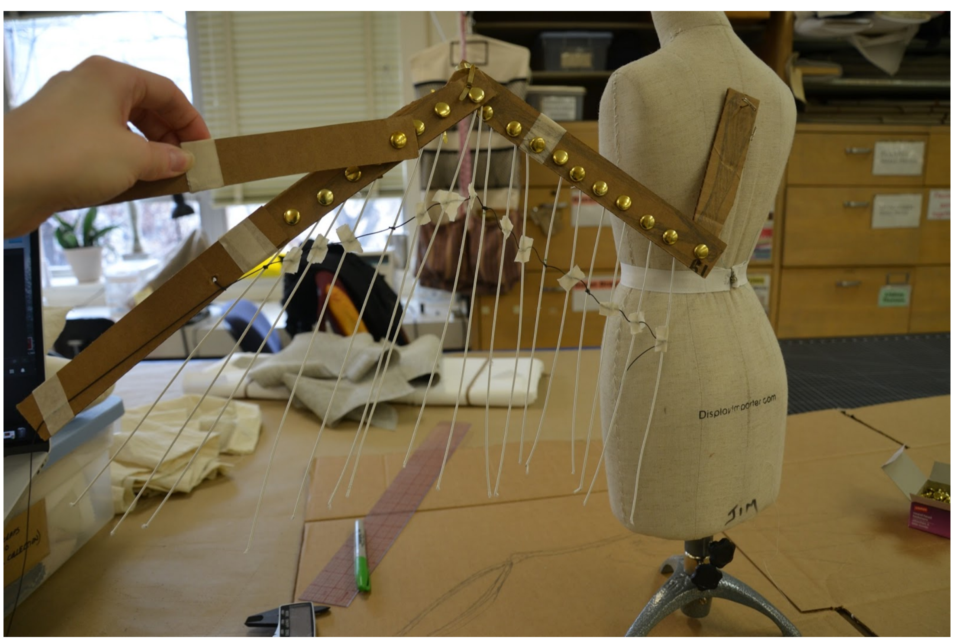


Illustration 25: The first prototype, made of cardboard, brads, wire, and tape.

This version established whether or not the size and ratios of the wings were correct. I experimented with how many feathers would be sufficient to communicate the design without adding too much weight or unnecessary elements. My first guess of 18 feathers in this version was way more than needed, and I reduced the number of feathers accordingly. This version also drove home the importance of the guide string that connects the feathers. This string serves as a control for how the feathers move in relation to each other. Because the string is anchored at specific lengths between the feathers, they will never gap or move past each other, and because they are all connected with one string, they move as a unit and unfurl much like the folds of a paper fan.

Finally, this prototype allowed me to experiment with the rod controller I had planned to use. I was able to play with what placement on the bones made the most sense for controlling the wing. As I played with this setup, I realized that the rod placement had everything to do with balance. Because the rod supports the wing from below and the performers' movements are largely horizontal, a lot of the nuance of the control had to do with how the wing balanced on the rod. If the rod was too far out onto the phalange segment (the segment mimicking the phalange or "finger" bones of the wing), then the wing collapsed under its own weight at the wrist joint. If the rod was too close to the wing joint on the phalange, then it was difficult to impossible to get the wing to fully extend due to the mechanical disadvantage of where the pivot point was relative to the "lever" of the wing.

THE SECOND PROTOTYPE

The second prototype stepped up the durability of the wings and introduced new elements. I modeled a simple version of the wings in Fusion 360, capturing the basic dimensions of the bones in height, width, and thickness. I also established the basic placement and spacing of the holes where the feathers would attach.

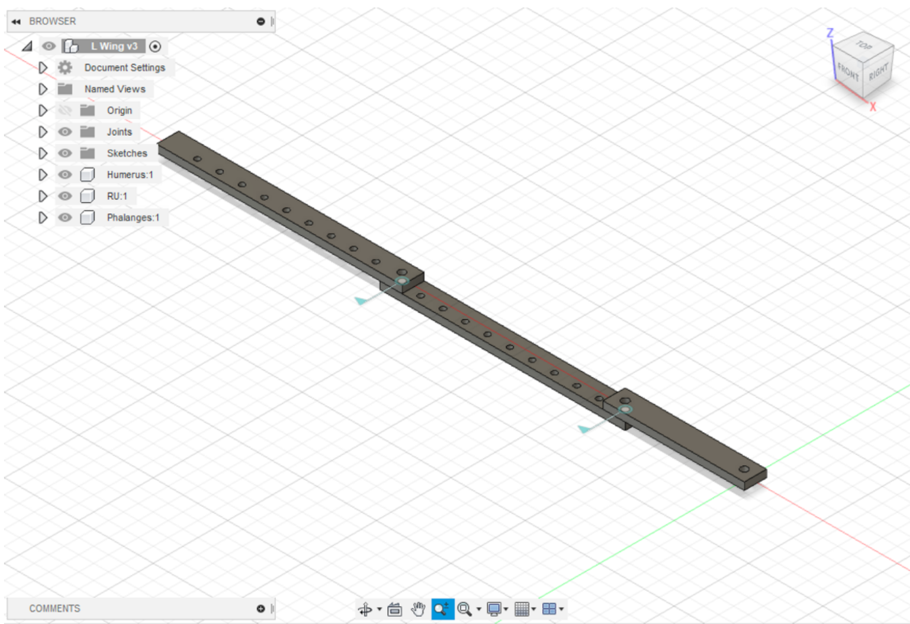


Illustration 26: The 3D model for the second prototype, at this stage just a rectangle with holes for the joints, modeled in Autodesk Fusion 360.

I didn't want to waste time shaping the bones of the wing before I had a better idea of the bone lengths and number of feathers. This version allowed me to establish some basic landmarks in the digital environment that could serve as the basis for the more polished bones later. I could also begin to experience the weight and durability of a 3D-printed object like this. Printing the pieces themselves took 2 hours and 45 minutes. I used a Lulzbot Mini 3D printer installed on The University of Texas at Austin campus in the Texas Performing Arts building. The Lulzbot Mini has a small bed size - 6”x6”x6” - which meant that I had to print my phalanges piece and my radius/ulna piece in two segments. It added a little bit of time to the process because I had to add to my model peg and hole features that would make connecting the two pieces more foolproof. With any 3D printer, whenever you need to print something that is larger than your print bed area, you either need to scale down or print your object in segments. Because these were just prototypes, I printed the pieces with a 60% infill. The infill amount determines how close to solid plastic your print is. For prototypes, an easy way to save filament and speed up print times is to print with a low infill. With these settings, and with the relatively small size of the pieces being printed, I enjoyed relatively fast print times. 3D printing really shines at this scale, when the pieces can fit comfortably into the bed dimensions and the shape of the objects being printed does not require additional support to keep the print stable.

This prototype also involved further development of the feathers. I had some inexpensive wire on hand that I chose to use for the shafts. I was not ready to dive into what the feather shapes would be made of, so I used the shortcut of masking tape sandwiched around the shafts and cut to the size and shape I wanted to try out. I knew that the final feathers would involve something that encased the shafts, which felt like a suitable facsimile of that concept.

For the elbow and wrist joints, I decided to use the bungee cord trick used by Nick Barnes for the joints of his puppets. The cord was sturdy enough to behave like a rod and allow the joints to bend, but they also provided durability and resistance to torque. Because they have flexibility in them, the wings could also bend off of the main axis of rotation in the joints and open up a wider range of motion. For the feather pivot points, I simply made a loop from the wire and that was held to the bones with a bolt, washer and nut. It evoked the rod and loop mechanism that I sensed would be key to this joint, without needing to go into the weeds on hardware just yet.

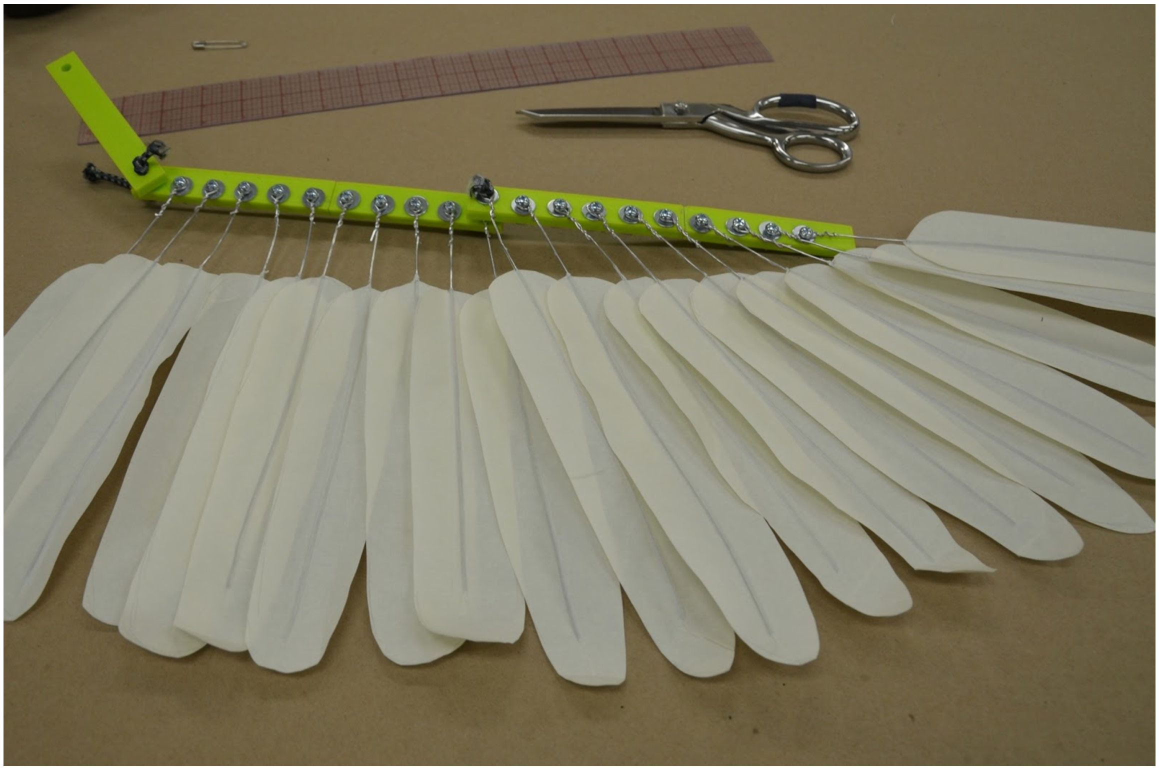


Illustration 27: The second prototype after printing and assembly.

I learned a great deal from this prototype. First and perhaps most important, it gave me the chance to better understand the feather stringing. In the first version, I had not added the feathers yet (just the support wires), so I did not have to work the string around them. When I first strung the feathers for this version, I laid the feathers down on the table and just tied the string around the shafts from one side. I had to pierce the tape feather to do so, which was great for keeping the string in place height-wise on the shaft. However, when I went to move the wings, the feathers did not unfurl properly. If I had looked closer at an antique fan, I might have figured this out sooner: if the strings are on one side of the feathers, then they stop the feathers from closing. For the wings to move properly, I needed to alternate the sides that the string entered and exited the feather. I also gained some insight into the type of string I would want for the final version, as the nylon string I purchased was too slippery and thick, which made tying them difficult and securing them more of a hassle.

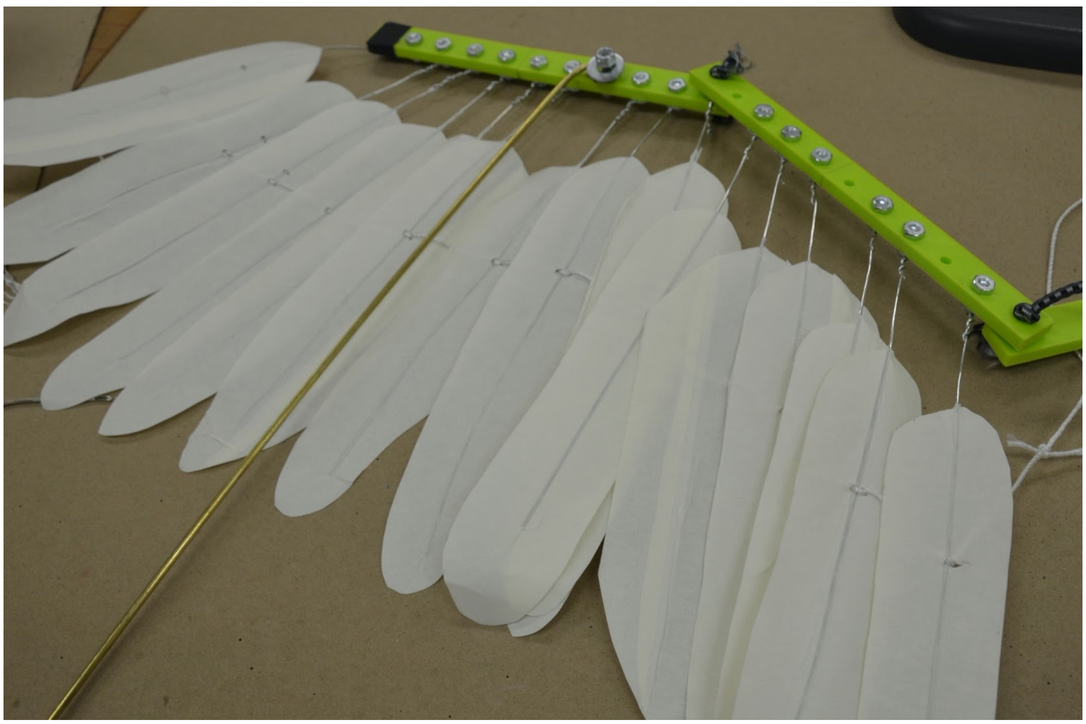


Illustration 28: The second prototype with the feathers properly strung.

I also eliminated three more feathers after assembling this prototype. With the tape added to fill out the shapes of the feathers, it was clear that the 16 that I had were just overcrowding the wings and adding weight without much benefit. I removed feathers where they felt crowded and noted that I would have to redistribute the hole placement in the wings for next time.

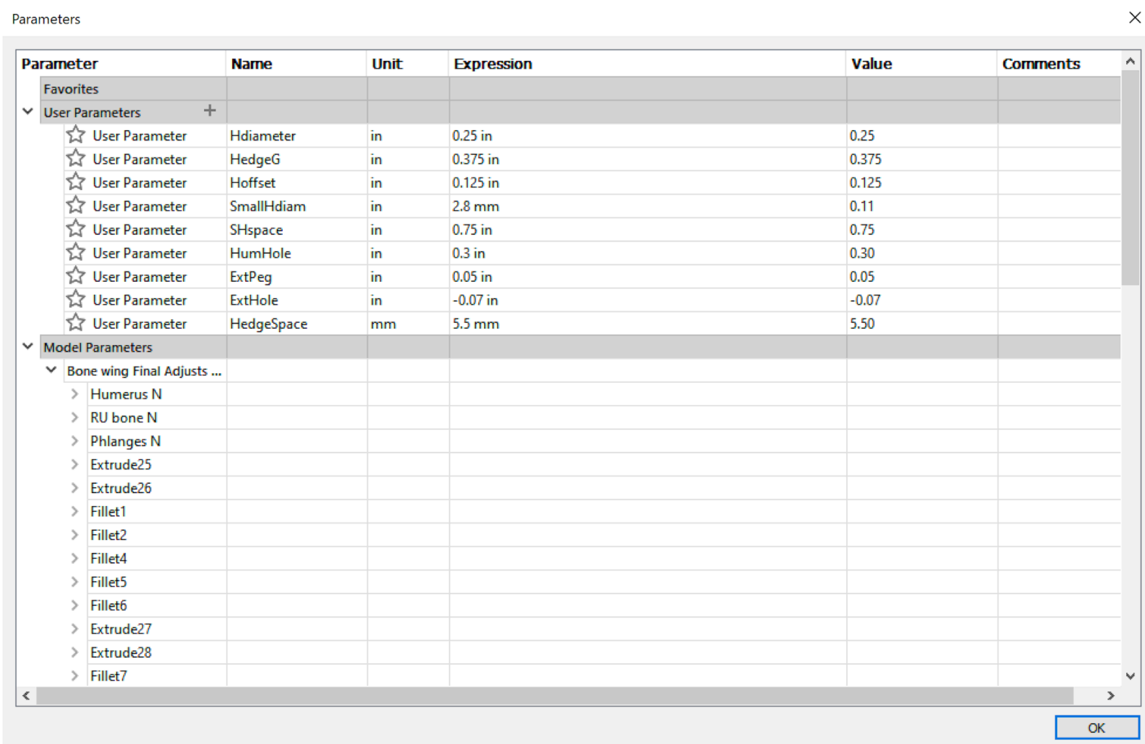
This version also gave me a great deal to think about in terms of the feather joinery. The nuts and bolts clearly were not what I was looking for. For one thing, they would not stay on. The friction from the wire loops' rotation slowly worked the nuts free from the bolts and would have required either adhesive or a locking nut to stop it. I wanted the wing joints to be replaceable, but not at the cost of security. They were also very bulky. I did not like how they protruded from the bones, disrupting the smoothness of the surface and aesthetically working against the streamlined look I envisioned. I knew that whatever I chose, I wanted it to look integrated with the wing as a whole, and to support rather than undermine the design. The search for the perfect hardware led me down a rabbit hole of different types of pin joints, from smaller nuts, to nuts that could recess into the bones themselves, to clevis pins, swivel joints, and more. I found myself getting frustrated, because it felt like I was coming up against a huge gap in my knowledge that was preventing me from testing materials fully. It also drove home another aspect of prototyping: cost.

Prototyping is so important in terms of perfecting an idea and working at different fidelities of a prototype can help reduce costs. However, it cannot eliminate the fact that you need materials to test with. For a student working independently without her own workshop, I found myself needing to run to the hardware store for all kinds of materials - nuts, bolts, tape, clips, different sized nuts and bolts, and so on. Overall, I managed to keep my costs relatively low, but there is definitely an access barrier for the casual maker or the artisan working in an under-furnished shop. In many ways, you need to "invest" in prototyping so that you can have a variety of materials on hand for easy access and the ability to try things on a whim rather than specifically plan for them and purchase them once you have fully considered them. It struck me as I ran out for all these materials that this was one of many ways that costume shops would face stumbling blocks in trying to implement this type of workflow.

THE THIRD PROTOTYPE

The third maquette was designed mostly to explore the bone shape. This version allowed me to start exploring the shape of the bones and continue to experiment with hardware for the feather attachments. The second prototype had helped me finalize the number of feathers that I wanted on the wings and where to put them - changes that were then adjusted in the model I had already created in Fusion 360. Now that I had a sense of the number and size of the holes, I could apply a more stylized and bone-like shape over them. This process can be a little difficult to follow without describing in better detail how the modeling environment in Fusion 360 works.

In Fusion 360, you are able to work in three different environments: the sketch environment, the modeling environment, and the sculpt environment. For most Fusion workflows, you start with the sketch environment. The sketch environment allows you to create forms with very specific dimensions and define them in ways that let you adjust them later with relative ease. Beyond just assigning dimensions, you can define the relationships between elements, such as the angle at which lines intersect, the space between elements, and so on. From this 2D environment, you can extrude shapes that are defined by the sketch. For my wing model, I had created the holes in my model on a line, guaranteeing that they were evenly spaced relative to the edges of the rectangles. I then assigned a dimension to the space between them with a parameter I saved in a window of dimensions, rendering them all equally spaced relative to each other. This parameters step is important, because having the value in the saved parameters window lets you go in and edit that value directly later. So, I had said my holes were “SHspace” apart and was able to adjust that spacing at will by changing the value of “SHspace”. I did the same thing with the diameter of the holes in the model. I knew that the size of the holes would depend entirely on the size of the rod in the feather joints, a dimension that I had not settled on yet as I tested hardware. Knowing that this value was saved in the log in Fusion meant that I could come back anytime and adjust the model as needed with a few clicks.



Parameters

Parameter	Name	Unit	Expression	Value	Comments
Favorites					
User Parameters					
User Parameter	Hdiameter	in	0.25 in	0.25	
User Parameter	HedgeG	in	0.375 in	0.375	
User Parameter	Hoffset	in	0.125 in	0.125	
User Parameter	SmallHdiam	in	2.8 mm	0.11	
User Parameter	SHspace	in	0.75 in	0.75	
User Parameter	HumHole	in	0.3 in	0.30	
User Parameter	ExtPeg	in	0.05 in	0.05	
User Parameter	ExtHole	in	-0.07 in	-0.07	
User Parameter	HedgeSpace	mm	5.5 mm	5.50	
Model Parameters					
Bone wing Final Adjusts ...					
Humerus N					
RU bone N					
Phlanges N					
Extrude25					
Extrude26					
Fillet1					
Fillet2					
Fillet4					
Fillet5					
Fillet6					
Extrude27					
Extrude28					
Fillet7					

OK

Illustration 29: An example of the model-generated parameters and user-generated parameters in the Fusion 360 workflow. All of the User Parameters can be altered directly in this window.

This is one of the things that makes Fusion 360 such a powerful tool. You are able to build adaptability into the workflow of your modeling, easing the burden of alterations later. I would encounter many moments like this as I prototyped and modeled in Fusion 360 for this process. I cannot overstate how much headache it reduces, and how much confidence it gave me to simply generate objects rather than throwing all of my energy into one high fidelity prototype. In the end, because making the maquettes was relatively simple, I could devote more energy to problem solving and testing rather than the actual fabrication.

Because I had established my holes in the second maquette, I was able to simply create a new sketch on top of the holes, knowing exactly where they were going to be and the size that the wings needed to be. I also changed the hole size to test out the clevis pins I had ordered to test for feather joints.

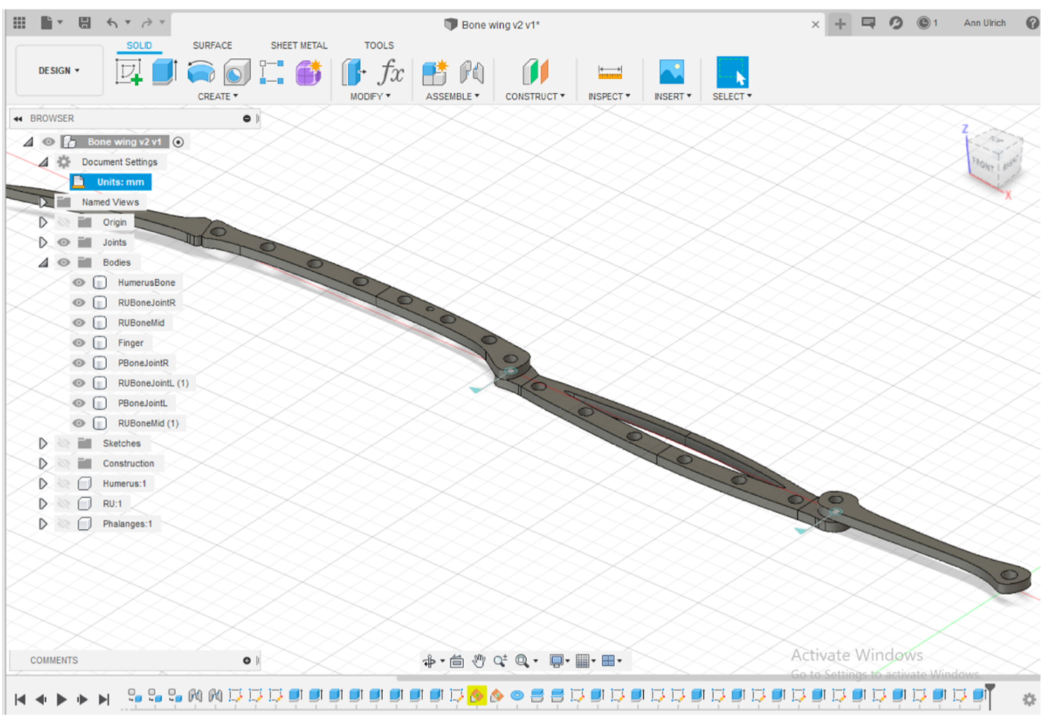


Illustration 30: The model for the third prototype in Fusion 360.

As for hardware, on this prototype I was testing clevis pins as an alternative to nuts and bolts because they have a lower profile and a slightly more permanent locking mechanism that could be undone with pliers. I also ordered a special ball and socket joint (see Ill. 29) with a channel for a threaded rod that could serve as the attachment point for the controller rod. This rod joint needed to be incredibly sturdy, as this connection moment was where all the controlling would happen for the puppeteer.

The print time for this prototype was slightly longer - 3 hours and 30 minutes - because the phalange and radius/ulna pieces of the wings were slightly larger. I again employed a lower infill to keep print times fast. Again, I had to print in two pieces for the phalanges piece and the radius/ulna piece. After printing, I used the bungee cord to attach the joints to each other and examined their overall look and thickness I had taken an educated guess at. Upon inspection, I found that a segment of my “radius/ulna” segment was too thin. The section was too easy to bend with pressure, and lacked support, so I knew I would need to thicken the section and make the hole I had modeled into the segment smaller. The “humerus” segment also seemed like it could be a little thicker to be certain of its durability.

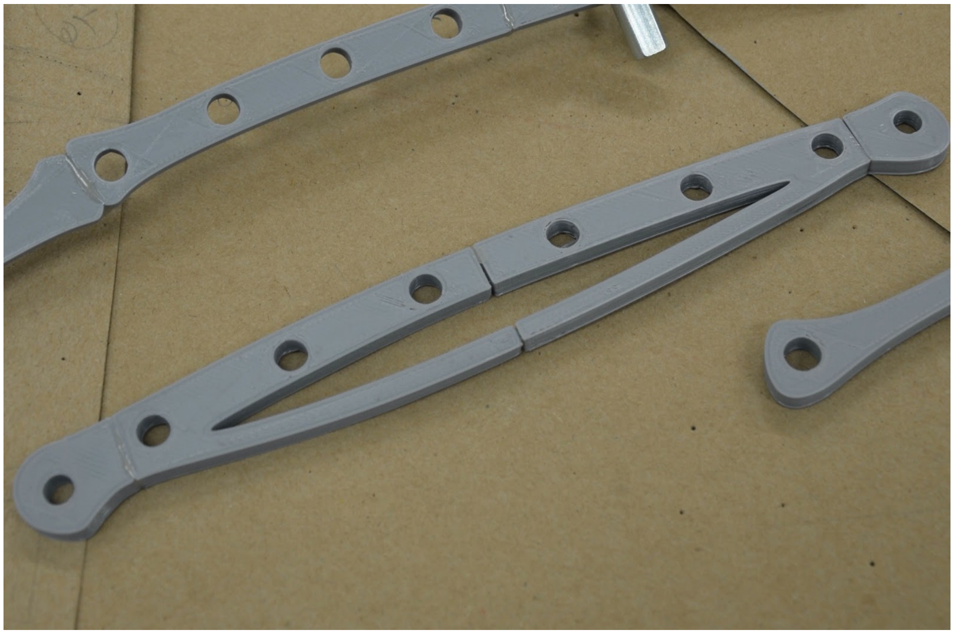


Illustration 31: The weak area of the radius/ulna bone.

As for the wing hardware, I was unsatisfied with the clevis pins I had ordered. They were more subtle than the nuts and bolts, but they still felt too at-odds with the overall design of the wings. The swivel joints I was looking at were not satisfactory for the same reasons as well. I also knew for the next prototype I had to address the question of the “shoulder” joint, or the joint that would need to pivot as well as rotate. I had been thinking about the joint that Nick Barnes had used for his angel wings, and how they had just used an industrial strength clip to attach the wings to a loop. The scale of these wings was smaller, so I did not need anything as involved as the clip they used, but I liked the idea of the shoulder joint as an opportunity to attach and detach the wings. Design-wise, it occurred to me that I could also use the removable wings as a chance to save some time and effort with regards to the owl head for the costume. If the wings could attach and detach, then I could use the same head for the small and large versions of Lechuza and save the effort of replicating the head for two different looks. I shopped around and found some very small-scale S-clips, only about 1” long and ½” wide. I had been using a simple hole for all of my wing tests up to this point, but if I was going to add an S-clip, I knew I could create a more elegant housing for it.

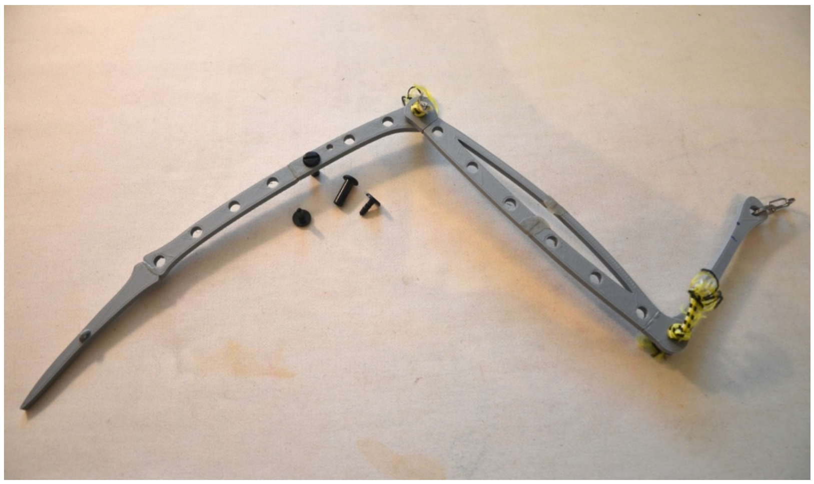


Illustration 32: The third prototype and rejected clevis pins.

Illustration 33: Closeup of the “shoulder joint” configuration.

THE FOURTH PROTOTYPE

It was time to start the fourth prototype. I knew the tweaks I had to make to the bone shapes, and I had a plan for creating a custom housing for the S-clip. The only major problem to solve in terms of the basic structure of the wings was the joinery for the feathers.

At this point, I sought the advice of The University of Texas at Austin professor and scene shop manager J.E. Johnson, to see if there were any hardware suggestions he had. After talking through my frustrations and the qualities I was looking for, he offered what would be a revolutionary solution for me: make the joints myself. I had dismissed this idea earlier, because I did not think that I could print pieces strong enough to reliably handle the stress of live performance. However, it was an idea I had not tried, and J.E. encouraged me to explore the possibilities. We sketched up the start of different ideas together and felt excited about the possibilities of a "U" shaped joint that would essentially hug the bone by gripping it with tabs recessed in holes in the bones, and the feather shaft would extend off of it.

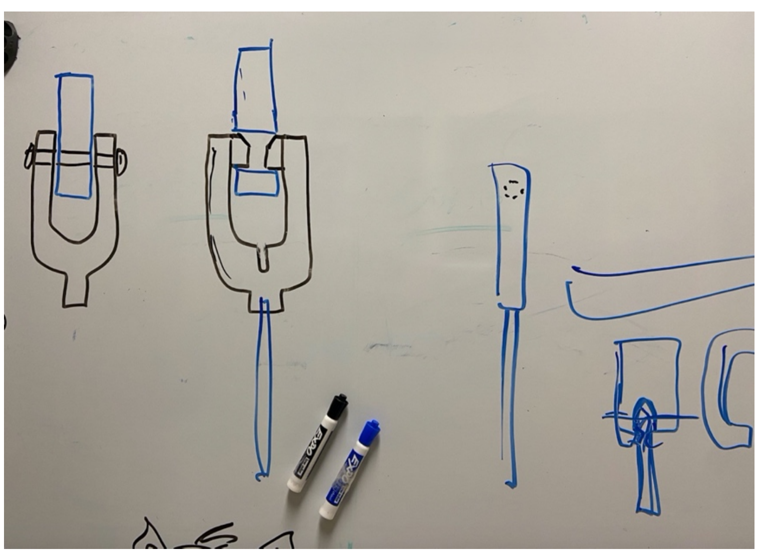


Illustration 34: The early U-Joint sketches discussed with J.E. Johnson.

The advantage of this joint was that it centered the feather underneath the bone rather than pushing it to one side of the bone, which would both look more logical and also likely prove to be more stable. I quickly rendered a joint based off of our discussions. The initial design test revealed a few flaws: the peg shape I had created to snap into the recess in the bone were too shallow and slipped out easily. I printed another joint with longer pegs to solve this problem.

This second version revealed another problem: my initial sizing for the arms of the joint were too thin, and after successfully snapping them into place and removing them a couple of times, one of the arms broke. Feeling like this idea still had potential, but that it needed some serious edits, I considered the problem: the arms of the U-joints would always be the weakest part of the joint and forcing them wider in order to install them was foolish. Even if I increased the size of the arms to make them sturdier, they would eventually become too bulky and bring me back to my original problem of visual clunkiness. Sturdier arms also ran the risk of being impossible to attach to the bones if they would become too inflexible to snap into place on the wings. I still wanted the joints to be easily removed and replaced, but my current design was unreliable.

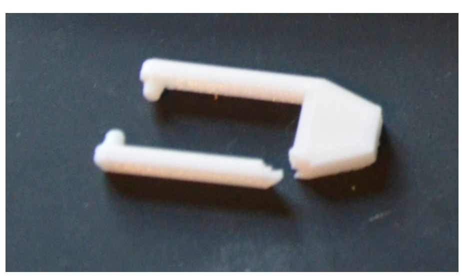


Illustration 35: The second failed U-joint test with a snapped arm.

I realized that I could combine this new hardware attempt with my old attempts and take what worked from the nut/bolt arrangement and add them to the U-joint. Instead of a gripping notched piece that had to snap into place, why not thread a rod through the bone that was held in place by the arms of the U-joint? This would mean most of the stress was on a strong metal rod, I never needed to bend the arms of the U-joint, and all I had to do to remove a given feather was slip the rod out of the pivot hole. With this new design in mind, I modeled a new prototype. This time, since I was feeling confident in the mechanism, I spent more time building some design into the shape of the piece. I sketched different shapes before setting on a more "V" shaped design, that had a recess for the shaft of the feather in the base, and a more tapered almost feather-esque line to them. One of the arms of the V-joint had a hole in it that went completely through, while the other had a hole that ended inside the V-joint arm. This would allow me to insert the rod through one side, and have it held securely in place on the other side.

I quickly put these ideas to the test. I was satisfied to find that the relatively simple shape of the V-joint came together in a couple of hours. It printed relatively easily, and because of its size it printed quickly - only about 40 minutes per V-joint. My friend and fellow student Bill Rios had a 3D printer in his house and was kind enough to do most of my printing at this point in the process. His printer, a Creality CR-10, had a larger print area than the Lulzbot minis. The 12"x12"x12" print bed meant that all of my bone pieces could be extruded in one piece now, saving me the trouble of adding joinery and gluing pieces after they were printed.

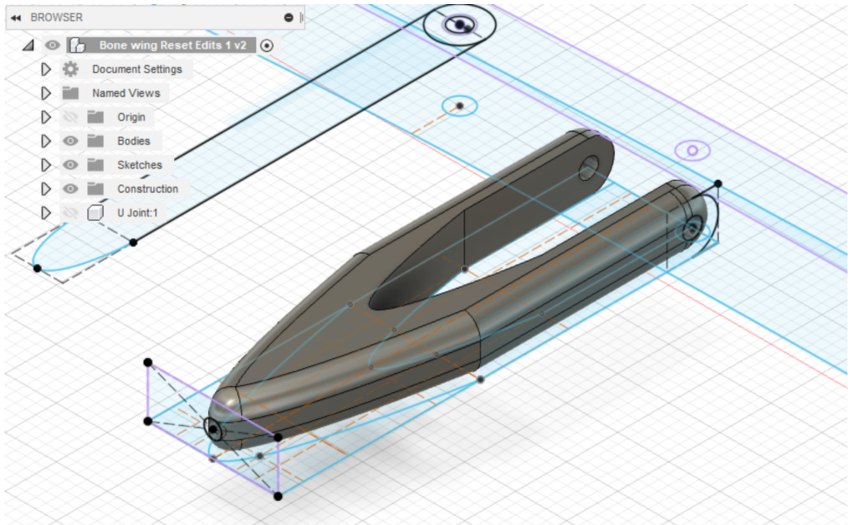


Illustration 36: The V-joint modeled in Fusion 360.

Meanwhile, I adjusted the radius/ulna segment to be sturdier. In the Fusion 360 workflow I was using, that kind of alteration happened at the sketching step of the workflow. A 2D sketch of your model is rendered, and then you extrude a three-dimensional form from the sketch. This body created follows the profile of the shape you have rendered. What is great about this workflow is that you can adjust the sketch after the body has been extruded and the body will change with the sketch. So, to create a sturdier structure, I went into the sketch for the radius/ulna segment and adjusted the outline of the thinner area to be thicker and more durable. The trouble I encountered was that I had not set up the planes of my sketch properly. The sketches from the second prototype were still underneath the new bone shape sketches from the third prototype. Because of this, adjusting the sketch did not work properly. The lines from old sketches interfered with alterations to the current sketch, and deleting the old sketch meant painstaking and careful selection.

Another problem came up when I tried to make the bone segments thicker. Again, this is usually an easy fix where you can go into your workflow and edit the dimensions chosen for the extruding step of the modeling. Instead of extruding a body 12mm from the sketch plane, you can edit the action to be a 16mm extrusion. However, because I had offset the sketch planes for the three bone segments based off of the thickness chosen for the second prototype thickness, I could not change the thickness of the bones without compromising the planes referenced by the sketches. To put it another way, the planes that the bones were sketched on were tied to reference points based on the thickness of the bones, and to alter those reference points compromised the sketch planes because their referenced geometry no longer existed.

It ended up being easier scrapping the sketch and starting over. A frustrating development to be sure, but it drove home the importance of having a good foundation in workflow for your models. The silver lining of the situation was that at this point I had internalized the steps for modeling the bones. I had all the numbers and ratios and bone shapes established, so it was only a matter of recreating them without my earlier mistakes. Because there was no development needed, it only took a couple hours to recreate the bones from the ground up. For costumers considering adopting these tools into their own practice, it is good to know that there is a learning curve to using modeling software. It takes a good amount of time to fully absorb these workflows beyond the simple understanding of the digital workspace. A good amount of patience and a willingness to fail from time to time is essential, something we are not always given the opportunity to do while at work.

Once I had reset my model with a better foundation, I applied the changes that I had decided on from the third prototype. I thickened the decorative segment on the radius/ulna piece, made all of the pieces thicker overall, rounded the edges so that they had a properly organic look, and I added extra thickness at the elbow, wrist and shoulder joints. This served two purposes: it evoked the way bones tend to thicken and become club shaped at the joints, and the extra thickness allowed for more durability at a stress moment. I also created space for a cavity to house the S-clip for the shoulder joint. Using the dimensions of the clip as a guide, I modeled the cavity with a hole that passed through the whole bone. This way the clip could be inserted, and one of the clevis pins from the earlier failed test locked the clip in place.

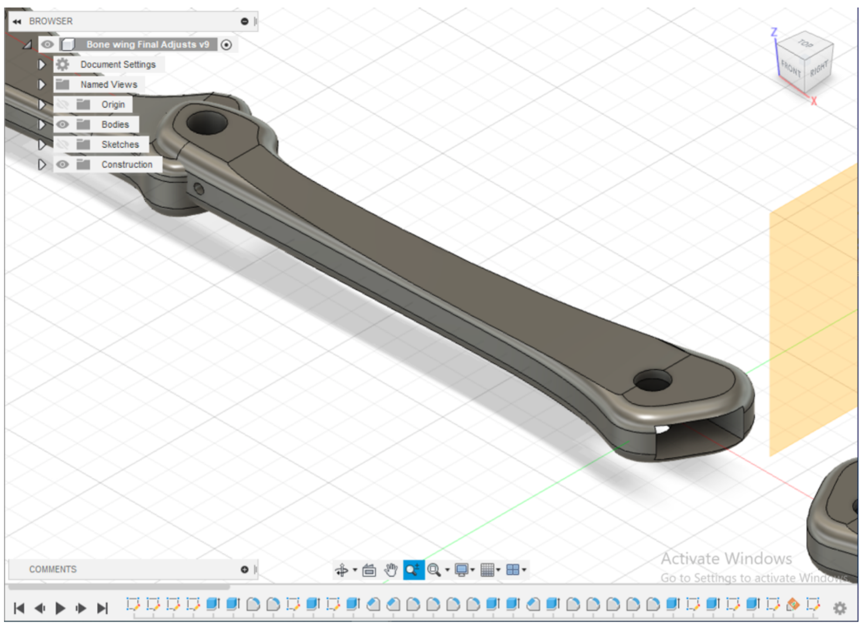


Illustration 38: The new “humerus” bone with a special modeled cavity for an S-clip to insert into.

As all of the edits were happening to the bird wings, I was also moving forward on the wing feathers. For the third prototype, I decided to try using EVA foam as the base for my feathers and sandwich the shafts to the foam with fabric. The *Angels in America* wings and other cosplay feathers I had seen used the same sandwiching technique. Given that, I was fairly confident that would work here, but I additionally wanted to make sure the feathers were crumple resistant and durable in addition to being securely attached to the wire. EVA foam is known for its durability, affordability, and for being lightweight. I used contact cement to apply lightweight fabric to the EVA foam with the wire placed between the two. The fabric offered the additional benefit of a nice painting surface for the feathers. My tests worked better than I had hoped. The contact cement held the wire securely in place, resisting my best efforts to pull it out. The fabric also helped protect the EVA foam from tearing. The foam was already fairly durable and resistant to tearing, but the fabric added extra resilience and made damaging the feathers impossible without cutting tools.

The other advantage of EVA foam was that it afforded another opportunity to use digital fabrication. I imported an image of Spotted Owl Feathers into Adobe Illustrator and traced around their perimeter to create my feather shapes. I selected a few feather sizes so that I could properly mimic the gradual reduction in feather size you see on real bird wings. Once I had these vector images, I loaded them into the laser cutter's Retina Engrave program and cut out enough feathers for one wing plus a couple extra - 17 in total. I found I could fit about 9 feathers in the cut area per session, and each cut took about 4 minutes to complete. It is truly miraculous how fast and easy laser cutters are. The EVA foam cut especially well, needing only one pass with the laser at its highest speed setting.

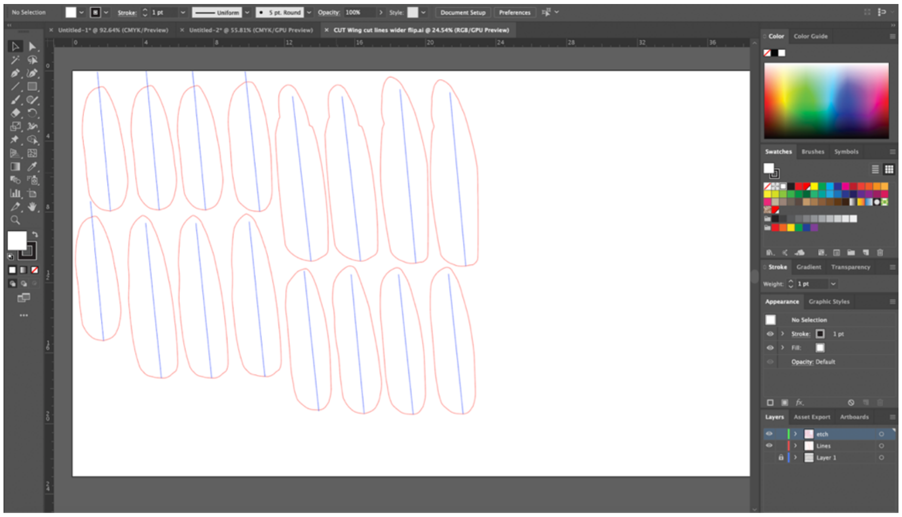


Illustration 39: The test feathers in Adobe Illustrator.

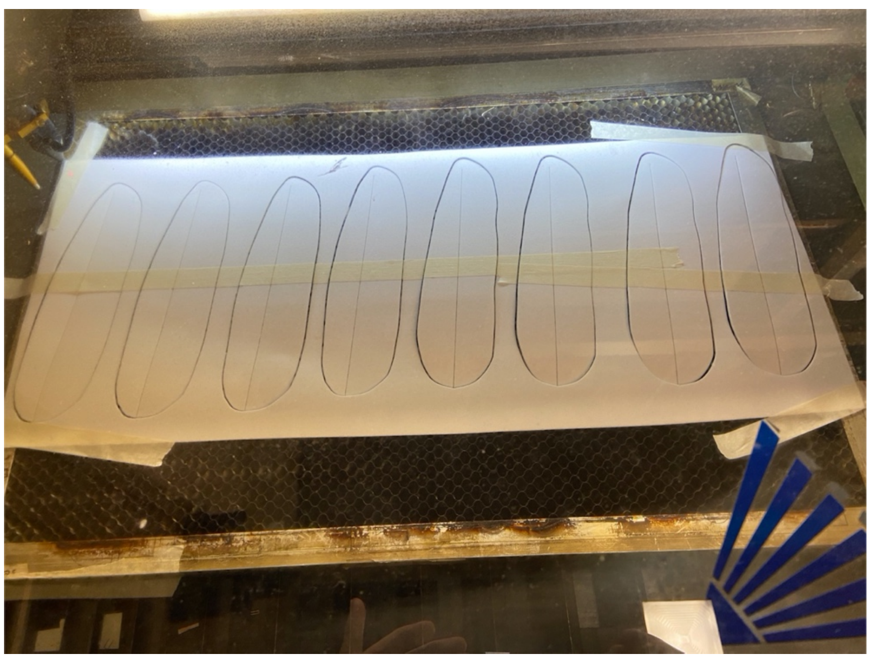


Illustration 40: The test feathers after being cut. The masking tape helps stabilize the foam so it does not spring up after being cut out.

Now there were a few analog steps to complete. The spring steel wires had to be measured and cut by hand and glued to the feathers and fabric. The shafts of the now-assembled feathers had to be glued into the holes at the base of the V-joints. Then the V-joints were attached to the bones. Small segments of the same spring steel used for the feather shafts were used to thread the bones and hold the joints in place. Because this was still a prototype, I chose to temporarily attach the feathers to the bones. Instead of closing the open hole in the V-joint with epoxy as I planned to do, I simply used small pieces of gaffer's tape to keep the rods from falling out (see Ill. 43).

Illustration 41: Assembling the test feathers. The fabric is adhered to the EVA foam and the wire is sandwiched between the foam and fabric.

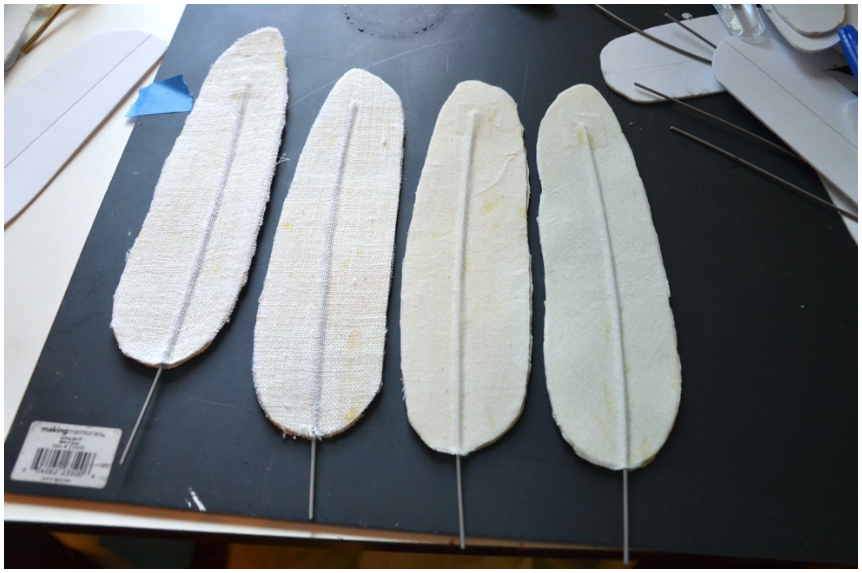


Illustration 42: The test feathers with cleaned up edges.

Illustration 43: The feathers with the attached V-joints, temporarily held in place with black gaffer’s tape. Segments of the spring steel for holding the V-joints in place can be seen on the right.

Finally, the last step was to string the feathers. This the final analog step in the process. The system I had for it was to lay the wings flat on a table, and then arrange the feathers into the spacing I was looking for. While flat on the table, I went through and tied each wing one at a time, using a needle to pass the string directly through the EVA foam. For extra security, I applied a little bit of white glue to the knots I tied around the wire to keep them from loosening (see Ill. 44).

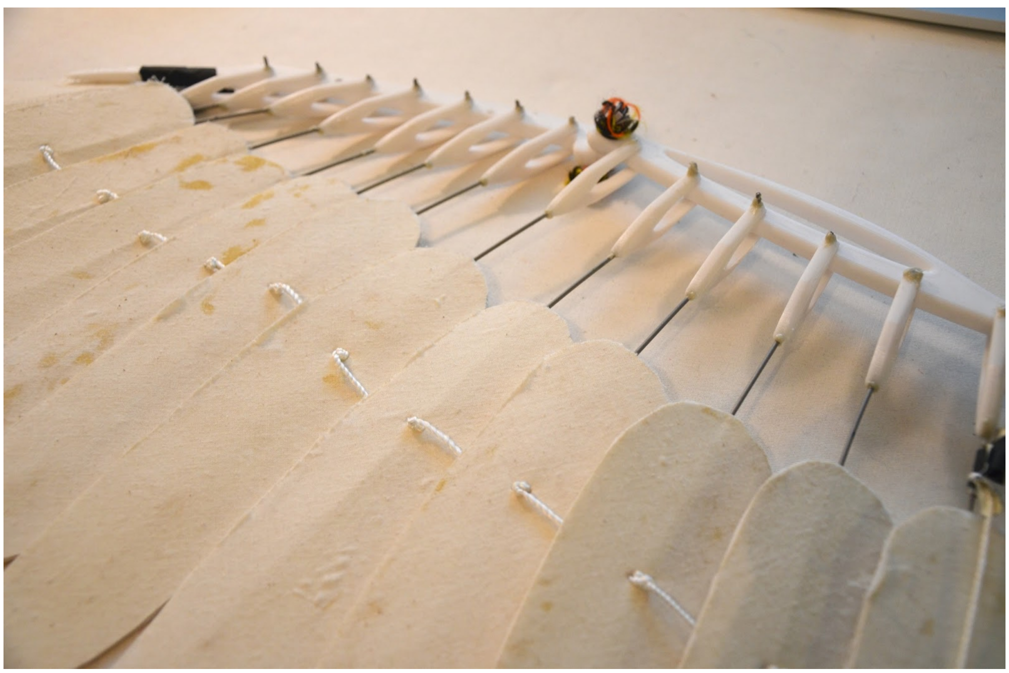


Illustration 44: The strung feathers.

I also upgraded the controller rod from the nut/bolt and looped wire setup from before. The rod controller needed to pivot side to side much the same way that the feathers did. It was going to receive the most stress of all the joints on the wing, so it had to be sturdy. A ball and socket joint made of steel seemed perfectly suited to the task. The style I purchased came with a threaded hole where a rod could be inserted, and since I already had brass controller rods on hand, I simply had to use a die threading tool to carve threads into the rods. Now the rods could be easily attached and detached by unscrewing them from the ball joint.

Illustration 45: Using a die tool to carve threads into the ⅛” brass rod.

This prototype felt like it was finally approaching what I had been imagining from the beginning. The overall look was sleek and unified, and fitting for the design of the character. The feathers were folding and unfurling as I had hoped. And they were durable. The spring steel rods for the feather shafts were stable, the 3d printed parts were sturdy, and the feathers themselves resisted damage from rough handling. It felt ready to get into the hands of the performer who would be operating them. So, I contacted Marina DeYoe-Pedraza, the actress and puppeteer playing Lechuza in Cucuy. We set up a meeting time to try out the head in the context it would be used in for the performance. The owl body structure was placed on a base that rests on the head, and the wings were clipped to that base. With the wings secured to the head, Marina was able to operate them with the controller rods.

Illustration 46: Performer Marina DeYoe-Pedraza testing out the wing placement on the head base.

Overall, Marina found the wings to work fairly well. The main feedback she had in terms of working with the wings was that the rod controller needed to be longer and easier to hold. The ball joint connected to the rod was also harder to work with than expected. Because it had some give to it up and down, when she tried to tilt her hands to get the wings to pivot and flatten out she had to move her hands very high up in order to get the angle needed. Often constraint is a handicap for puppeteers, but in this case the flexibility of the joint meant more work for the puppeteer. She also found the feathers closest to her neck collided with her shoulder. She had some trouble with the collapsing/folding motion, that I suspected had to do with the S-clips being under-constrained at the shoulder. Part of what makes the wings work in both directions is being able to push against the shoulder joint to get the phalanges to collapse inward. Without a sturdy hole for the shoulder joint to recess into, the wings are harder to control. Even with these notes and edits to take, I felt ready to move into the fourth and hopefully final prototype.

THE FINAL PROTOTYPE

The fourth prototype was fabricated with the assumption that it could be the final version. The bones were printed at a higher infill/density than the previous models, meaning that they were closer to a solid piece of material. Again, Bill Rios printed the bones out for me, this time using a Proto-plasta's high-temp carbon fiber PLA filament (htp21705-cf). This filament type is supposed to be more durable than normal plastic filament, due to the stiffness the carbon fiber adds to the material. Manufacturer specs describe its tensile strength to be 9,800 psi, compared to pure PLA (7,250 psi) and ABS (4,200 psi). You can also strengthen the carbon fiber filament through a process called annealing. An object is heated to a temperature above its crystallization point but below its melting point, causing the molecules to arrange themselves into larger and more durable crystal structures. The object is then cooled slowly, allowing the new crystal structures to be preserved. The supplier suggested annealing the prints in the oven for an hour, but I was nervous about not being able to closely monitor whether the prints were warping so I instead carefully heated the prints with a heat gun. I may still revisit annealing with an oven someday, but I did find that even with the heat gun it was alarmingly easy to go too far and melt the pieces slightly. Still, even without the precision of the proper equipment, I noticed a difference between the heated and unheated pieces. After testing the process on one of the V-joints and comparing it to untreated joints, the heated joints were noticeably more resistant to bending. 30 V-joints were printed out in four stages over 23 hours, 13 for each wing with two extra pieces to have for testing and unexpected changes. The set of three bones took about 19 hours, or 38 hours total. The higher infill dramatically increased the amount of time it took to print the pieces.

For the feathers, I switched to black EVA foam and a black lightweight cotton fabric, so that I had a dark neutral base to build up color onto for surface finishing. I cut 39 feathers so that I would have test feathers and extras. Each round of cuts (between 9 and 12 feathers) took between 4 and 4:30 minutes, and overall the process took about 45 minutes with the time it took to reset the EVA foam for each cut.

Illustration 47: The radius/ulna bone printed with carbon fiber filament.

Illustration 48: The high-fidelity feathers cut in black EVA and covered with black batiste fabric.

It occurred to me when looking at the third prototype that I should address the knots of the bungee joints. The joints were still working as intended with the bungee cord connections, and I wanted to continue using them. However, the bungee stayed in place by tying knots to stop the cords from passing through the holes. Those knots then rested on the surface of the bone. I thought for this model that I would try creating a recessed hole so that the knots would recede into the bones a bit and be less visually obtrusive. This was a simple fix in Fusion 360 that only took a few minutes. When I went to assemble this model, I found the knot recess worked exactly as intended, but with an unintended consequence. Because the knots sat recessed into the bone, tying the knots to the correct length that held the bones together with enough tension was quite difficult. I had to pull the cord out of the hole so that I could even tie the knot, but because I was pulling on the cord already, getting the knot to land at the right place was quite tricky. It did work in the end, but not without some sweating and swearing! If the knots had proven impossible to get right, I likely would have looked into material that could be adhered to the cord and add bulk to the cord without the need for a knot. Epoxy putties could be an option to explore in this case.

I also had to deal with the “lead” feather, or the anchored feather that was fully attached to the phalange bone. This feather is the first feather that unfurls when the wings open, and it pulls all of the other feathers along with it. Since the lead feather was already attached to a spring steel wire, it seemed logical to create a recess in the tip of the phalange that the wire could be inserted into and secured with epoxy. This edit and a slightly less bulky tip for the humerus bone at the shoulder to increase range of motion were the final two edits made to the model and were fairly simple to execute.

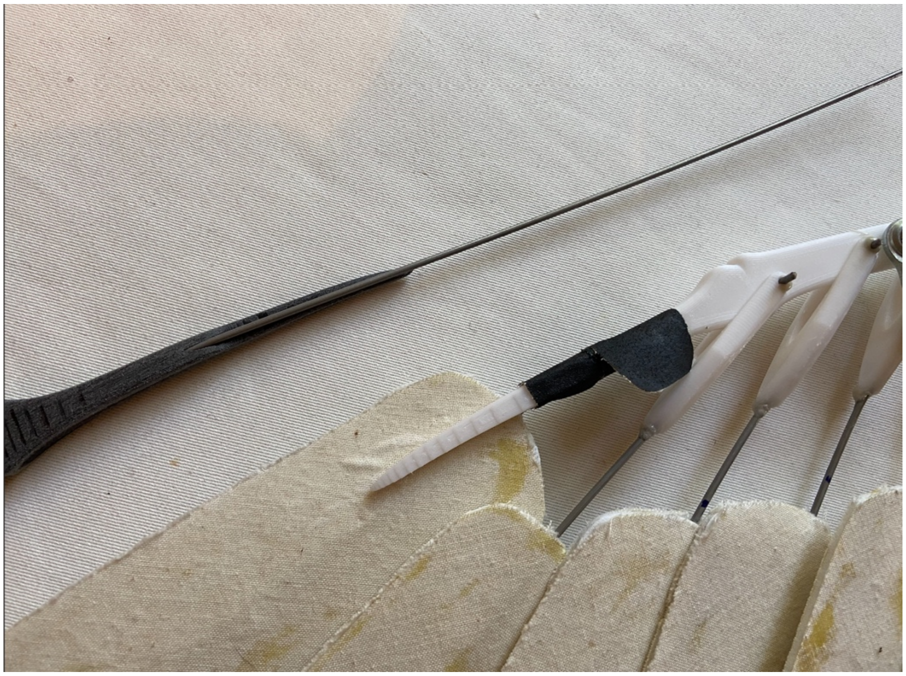


Illustration 49: The newly modeled wire recess in the carbon fiber print (left) next to the temporarily taped version from the third prototype (right).

Finally, I had to solve the problem of the rod joint. I needed a piece of hardware that had a threaded hole for a rod to insert into, that could pivot back and forth much in the same way that the V-joints did, but that had enough stability to prevent the joint for torquing when the puppeteer tries to pivot the wings. I quickly sketched up an idea that took the same principles of the V-joint and adapted them for another function.

I figured I could use the same spring steel I had used throughout the wings already, and have 3D printed pieces to trap the wire through the wings. The "front" half of the joint could be a simple cap, something that kept the spring steel in place and was big enough to bond with the epoxy adhesive. The back needed the hole for the rod, and it needed a hole for the wire at a 90-degree angle to the rod, and it needed to meet the bone with enough surface area to keep the joint stable.

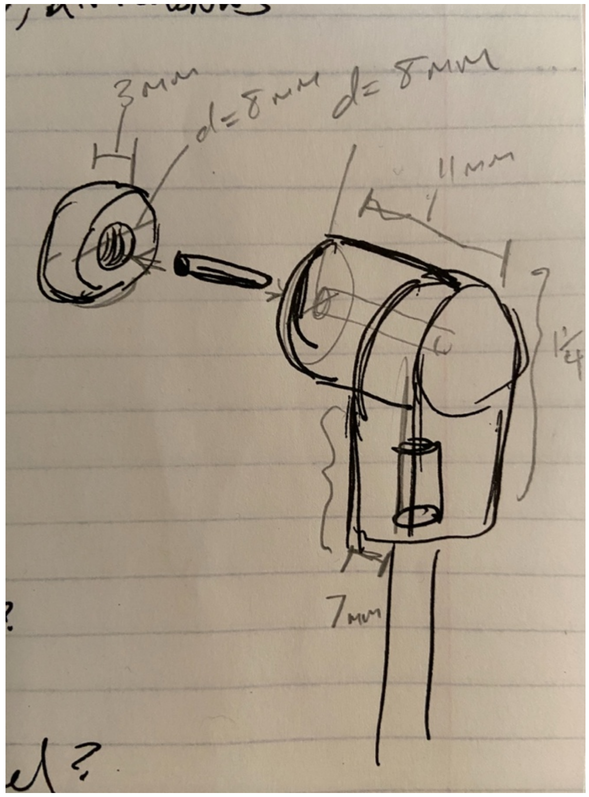


Illustration 50: The initial brainstorming sketch of the rod joint.

From my sketch I quickly rendered the rod housing and the cap in about 2 hours. One very useful tool in Fusion 360 that I got to utilize for this piece was the threading tool. Fusion has a threading function, where you can apply the spiral threads you would find in a common screw or bolt to an extruded hole. All you need are the specs of the hardware you are working with, and you can get a perfectly matched piece to go with it. I had my ⅛" rods with a 6-32 thread from the previous model and was continuing to use them. They were printed out of the carbon fiber used for the rest of the wings and printed with 99% infill to make them as strong as possible. Even with the slower print time, the two pairs of joints took only 7.5 hours to print.

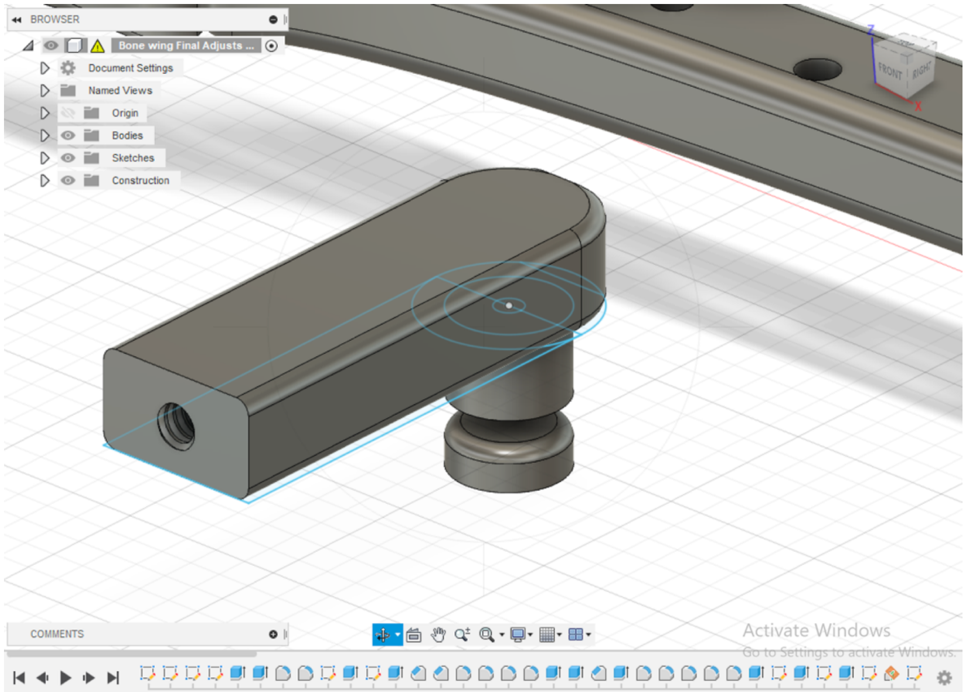


Illustration 51: The rod joint modeled in Fusion 360.

Having the wing model finalized, I could perform one of my favorite functions in 3D modeling: mirroring. As someone very familiar with analog or traditional sculpting and drawing practices, I can attest to how frustrating creating perfectly symmetrical things can be. It is even more annoying when the symmetrical object in question is going to be very obvious if it is not perfectly symmetrical. With the mirror tool in Fusion 360, a simple command created an entire separate set of wing bones, perfectly mirrored and with almost no effort. This meant that I ended up with six distinct objects to print for the wing bones. Those pieces were printed at 99% infill and took 35.5 hours to print.

With all of the pieces fabricated, I had to start the more analog steps of the process. In earlier models, I had taken shortcuts on the assembly stage to make assembly quick and also to make it easy to take the wings apart if needed. I still intended to have the pieces be possible to remove or replace in the event of damage, but now it was time to put components together in a more durable and polished way.

The bones and V-joints were sanded to eliminate the appearance of ridges and to give them a smoother surface. There were some pieces of support plastic stuck to the bones from printing that I used a Dremel to remove, then used a 150-grit sandpaper for the final rounds of smoothing. The bones were then painted with a simple acrylic paint mixture to get them to the proper bone-like color and texture. This paint was then sealed with a layer of white glue. The bones were attached to each other with the usual bungee cords, but this time the bungee knots were soaked in white glue to keep them from coming undone. When the glue had dried, the extra length on the bungee was cut down, a little more glue applied, and then the whole knot was painted to match the bones. The overall look reduced the presence of the knots dramatically. The S-clips were inserted the same way as they had been for the third prototype, except this time the clevis pins were painted to blend into the bones. The clips themselves, already dark in color, easily receded from view and were kept as such so that they could continue to have a low visual presence.

Illustration 52: The carbon fiber wings sanded, painted, and assembled. The S-clip has also been inserted and secured with a painted clevis pin.

Another rather analog step for the wings was prepping the wire for the feathers. The spring steel was very difficult to cut by hand with the medium-sized pliers I had access to. Still, I had to mark by hand and then cut by hand all 26 feather shafts, plus 26 small sections of spring steel that would thread through the V-joints and hold them to the bones. The tips of the wire that rested on the feathers then had to be ground down and smoothed so that they would not damage the fabric holding them to the EVA foam. Then the tips of the wire that would insert into the V-joint were sanded with 120-grit sandpaper and cleaned with alcohol to make their surface more likely to bond to the carbon fiber with epoxy. Next, the feathers had to be glued together with the spring steel shaft as I had done for the third prototype. Then a small amount of Loctite Plastic Bonder Epoxy was applied to the holes at the base of the V-joint, the shafts inserted, and left to cure for several hours. Once the epoxy was cured, the feathers were painted to add texture and the proper color to the wings.

Illustration 53: The feathers with bonded V-joints. A painted texture is being applied in acrylic paint with a chip brush.

A similar process followed for the segment of wire that connected the V-joints to the bones. The Vs were moved into place, then the rod was slid in through the V arm that had a hole in it. It continued through the bone to the other V arm, where it stopped at the blocked end of the other hole. The beauty of this setup was that the rod did most of the work in terms of handling the force of the feather pivoting. The only real trick was keeping the rod from falling back out of the channel it had been inserted into. To do this, I applied JB Weld Plastic Epoxy over the open hole in the first V arm. Once it had cured, the rod would be unable to slide back out, and the only way to remove the V-joint would be to break one of the arms, or more simply to scrape the epoxy away and remove the rod. The JB Weld cures into a spongier material than the Loctite epoxy, which cures into a hard and brittle substance.

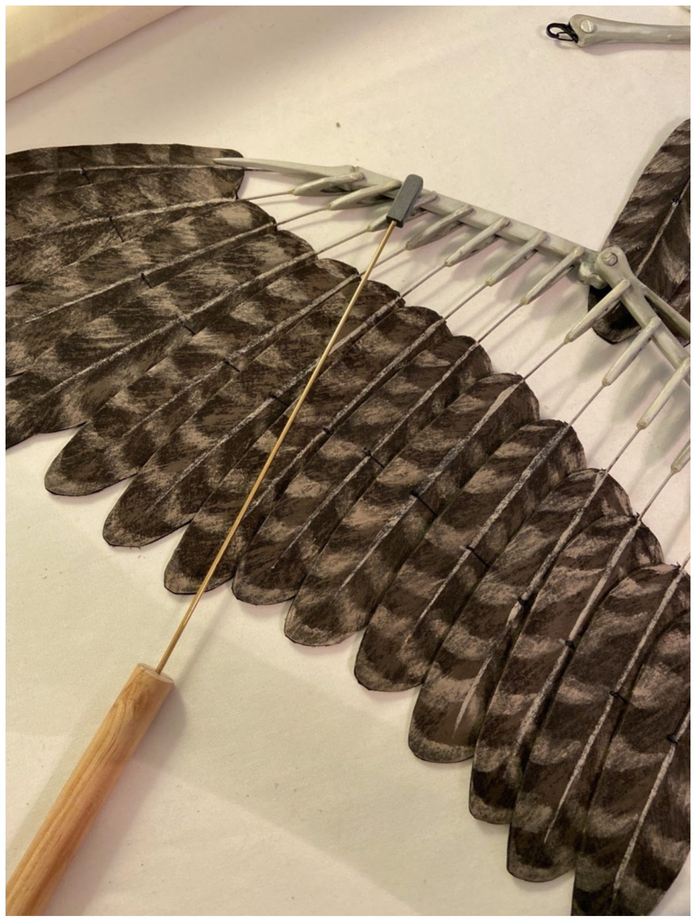


Illustration 54: The V-joints attached to the wing bones. The feathers have been strung with a braided black nylon string.

Finally, the last step was to string the feathers. Like before, I laid the wings flat on a table, and then arranged the feathers into the spacing I was looking for. This time I used a thinner black nylon string so that it would have a lower presence in the wings (see Ill.

54). I had noticed in the last prototype that when the feathers were opened quickly, they had a tendency to swing out and almost over-extend with the force of the opening. This could be mitigated by having the string anchored to the humerus bone after tying through the last feather. I had temporarily achieved that on the third prototype by taping the string to the bones, but this of course was not a permanent solution. For this model, I added a thin hole in the humerus bone just above the final feather. The string moved up the feather from its knotted point, then tied at the top of the feather to give the string a more subtle presence, before stringing through the whole in the bone. It was then kept in place by knotting it with a small bead.

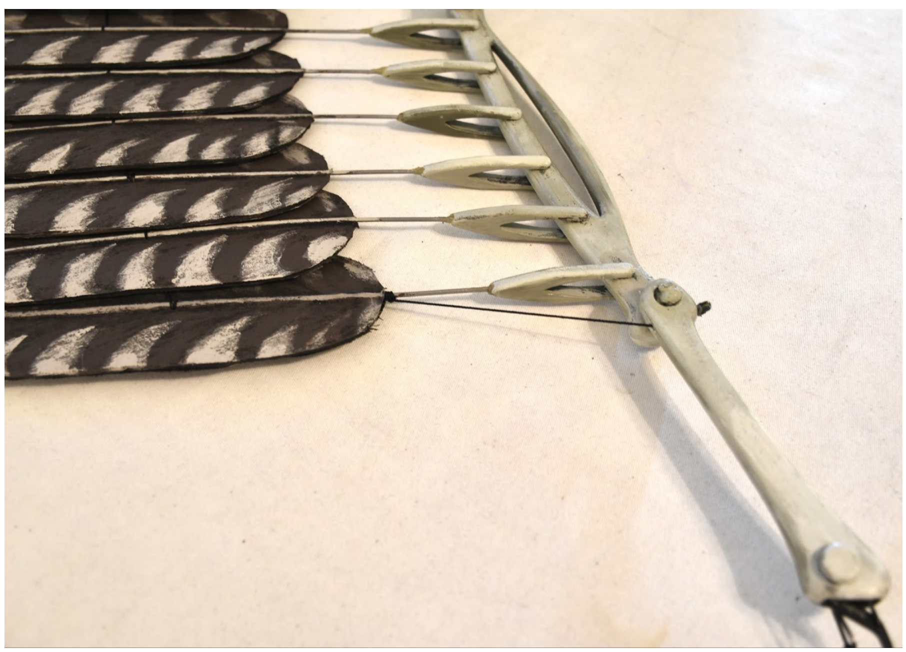


Illustration 55: The control string anchored to the humerus bone.

With the edits finished, the wings assembled, and the head and body closer to completion, it was time to have another field test with Marina, the puppeteer. The head structure had been partially assembled at this point, so we were able to clip the wings to the wire frame through a hole in the head base and confirm that the placement was working.

The wings already seemed to be working well. Most of my notes on costume had to do with the head and body rather than the wings. One of the few issues was that I modeled the cap for the rod joint too shallow and the epoxy didn't take. This would be a simple fix by modeling a slightly deeper cap to allow for more surface contact with the epoxy. But before the cap for the rod joint popped off, the new rod joint was doing a beautiful job of providing more nuanced control of the wings (see Ill. 54).

The other major development was a conversation about the control rods. As Marina experimented with the wings, she wondered how having longer rods might open up more options for movement. We also imagined together the possibility of having anchor points on her hips where longer rods could be secured, allowing Marina to move hands free with the wings tucked into a resting position. This would mean experimenting with other rod sizes and lengths, but this was a straightforward fix. Even if I ended up replacing the current rods with one of a different size, I could apply those changes in Fusion 360 to the hole in the model and print another joint.

Overall, it was thrilling to see Marina work with the wings. While working at home, I could do some degree of user testing with the wings and the head, but seeing a real professional explore how the wings operated and what was possible was truly inspiring. Movements that I worried would be too difficult to internalize came to her quickly over the course of her hour working with them. Watching the wings move from an observer position also let me truly see them as an "audience" member, rather than a technician assessing a product.

Illustration 56: Performer Marina DeYoe Pedraza testing out the fourth wing prototypes and the more developed head

In the end, assembling the final version of the wings took about 37 hours to make, adding up the time of sanding, painting, finishing, etc. It took 65.5 hours to print the bones, the 28 V-joints, and the two rod joints. The feathers took 45 minutes to cut on the laser cutter. The development of the wings is harder to quantify or translate to a professional work environment, as they happened in stages over months of a busy grad student work schedule. However, totaling up the hours, I spent 84 hours modeling the prototypes, developing the feather patterns for the laser cutter, and assembling and testing the prototypes. About 30 of those hours went directly to work modeling or adjusting 3D models. 32 hours total were spent printing the three prototypes. Harder to quantify is the amount of time that was spent mulling over the issues I was working with on each prototype. That kind of labor I was able to do while working on other projects, or to daydream about while commuting to school. In a professional environment, the timelines are not always so spread out, and it is possible that my passive development time would not have been so expansive. However, the nice thing about prototyping is that you are able to try many ideas out quickly, and on a tighter schedule I perhaps would have actually prototyped more as I ruled ideas out faster. Because my timeline was so long, I was able to assess how much I would be able to learn from a certain update, whether it could be combined with other updates, and if the update I was pondering even made sense to investigate.

I spent about $294 on materials for prototyping. This went to everything from gaffers' tape, nuts and bolts, assorted types of string, and so on. I used one sheet of 2mm EVA foam, currently priced at $10.74 (plus shipping) for the fourth prototype feathers. As I noted earlier, I found the cost of prototyping to be frustrating at times, because a lot of the prototyping cost went to materials that were ultimately never used in the final version of the wings. As a person who does not have a fully stocked studio at my disposal, I had to invest in the experimenting process. Nevertheless, those supplies were important for moving me forward on the prototyping journey. For the 3D printed prototypes, I used about 30g of PLA filament, or 0.03% of an average spool of PLA (currently priced on average at $20 at the time of writing).

The final version was much less expensive, with my main costs being carbon fiber filament, EVA foam, spring steel, and the adhesives for the assembly. Together, those supplies cost about $120. I used acrylic paint and white glue that I already had on hand, but those materials could be purchased for less than $20.

The pieces printed out of carbon fiber, including the extra pieces that were printed as a precaution, used 332g of filament, or about 30% of a typical 1kg spool of filament (currently priced around $40 at the time of writing).

Illustration 57: The completed wings attached to the completed owl headdress.

Chapter 6: Takeaways from the Process

I cannot overstate how transformative it has been to integrate digital fabrication into my practice as a maker and an artist. It is as if a new set of tools appeared that I now have access to on all of my projects. Included in this toolbox are the basic functions of digital fabrication - the ability to replicate objects with ease, the ability to perform basic yet essential operations like mirroring and scaling, and the ability to save perfect blueprints of work for future projects. Then there are the deeper and arguably more transformative workflows that I feel digital fabrication has illuminated for me, such as rapid prototyping. I can also feel the way that I think about and conceptualize projects has shifted knowing what digital fabrication makes possible.

Balanced against all of these qualities are the limits of digital fabrication and where I still see a use for the handmade and bespoke objects that we create for the stage. The learning curve for these workflows can be overwhelming when first starting out, and the sheer scope of the world of digital fabrication paralyzing without a guide or trusted advisor. There are processes that are simply better suited to traditional and intuitive workflows rather than mathematical and systematized ones. However, I think that when the two are married together you can create truly stunning objects.

Face-Value Qualities of Digital Fabrication

It seems only fitting to start my reflections with the most obvious benefits of digital fabrication. These are the tools and functions that have already been well-explored and catalogued elsewhere, but bear repeating here.

Creating custom joinery was one of the aspects of 3D printing that I found most compelling. Most of my work on complicated projects in the past was naturally limited by what materials I had available to use or limited by what I was aware of as options. The implications of being able to fabricate custom joinery for costume elements are enormous. In the same way that I was able to create custom V-joints for my feathers (see Chapter 5), I can create custom housings and joinery no matter the situation, and with an elegance that you cannot always achieve with repurposed or recycled items. This has especially useful applications in areas such as puppetry, but also can be useful in millinery and hat making, mask making, and jewelry fabrication.

Another important quality that digital fabrication provides is speed. Laser cutting in particular accomplishes in mere minutes what would take hours to execute by hand. I was able to cut hundreds of feathers for the body and head for Lechuza in under an hour (see Chapter 5). This has implications for work timelines, but also for the focus of the maker. When you aren't sinking hours into painstaking manual labor, you are able to focus on problem solving and development. You could argue that the final iteration of my bones was not a good example of a high-speed process because of the 65 hours needed to print all of the pieces. However, I would argue that because the time spent 3D printing is passive, it actually speeds up your process by allowing you to move other aspects of the project forward. While my bones were printing, I was able to laser cut my feathers, prepare the wire and fabric, and adhere them all together, as well as attach the V-joints, so that by the time the bones were ready, I was ready to fully assemble the wings. And, barring failed prints or unexpected print issues, you know that you are going to get exactly what you want from that print, cutting down time spent fixing errors or adjusting after shaping a piece by hand.

Another key quality of digital fabrication is its consistency. I was able to create 28 identical V-joints using 3D printing. I could count on my models to print or cut accurately from what was in my modeling environment. You can achieve this kind of consistency with molding and casting, but the skill of the maker and chance can come into play here. Air bubbles can form, the casting resin could be mixed improperly, or simple user error could lead to defective casts. Certain shapes do not always lend themselves to easy casting as well. My V-joints had small recesses and holes that would have made casting them incredibly difficult and time consuming. I would have perhaps had to create the V-joint without the hole and recess to allow the cast pieces to be removed from their molds more easily, meaning I would then have to hand-drill them afterwards anyway. In contrast, digitally fabricated objects will only fail if there is an issue with the equipment, or if the user did not follow best practices when creating their model. Being able to take the risk elements out of the process is a huge asset to any workflow.

Finally, there are some straightforward traits of modeled objects that seem unremarkable for people who work in digital frequently but are nothing short of miraculous for those of us who work with our hands. I noted earlier how I relied on my skills as an artist to create effective costume pieces, sometimes leaning on my ability to respond and improvise through a process. This approach can work well in a variety of contexts, but it can fall short when dealing with more left-brain processes like symmetry, scaling, and replication. I can use my observational eye and tools like calipers to see if something I'm sculpting is symmetrical, but ultimately that is a painstaking process and almost guaranteed to produce imperfections. Compare this to the mathematical power of a CAD program that lets you create symmetrical objects that you can be certain are perfectly symmetrical. The same rule can be applied to repeating objects or motifs.

Patterns become a simple matter of copying and pasting. Creating multiples of an object is not a problem. I was able to cut dozens of feathers for my wings and for Lechuza's body. I could print and use the V-joint knowing that it was perfectly symmetrical. When I created my final iteration for the bones, I was able to mirror them with the click of a button (see Chapter 5).

Finally, this mathematical computing allows you to easily perform another function: scaling. Instead of painstakingly taking measurements, calculating ratio equations and carrying out changes, you can scale an object by precise percentages. Again, because the functions are being carried out by computer, you can scale confidently knowing that the object is being uniformly transformed (or deliberately non-uniformly, if that is your goal). I was able to use this function for a larger iteration of my wings that happened after the small-scale ones were completed, when I scaled up my feathers and bones by 200%. It took little effort, and since it built off of previous models the overall time was minimal. Editing those scaled models for the second iteration took more time, but I did not need to start from scratch, ultimately saving time.

Rapid Prototyping

There were so many benefits to utilizing a rapid prototyping process to create my two pairs of wings. Perhaps one of the most transformative results of utilizing a process of rapid prototyping with digital fabrication was the way prototypes became tools rather than precious objects. Mockups for the stage can feel precious when they have taken time and effort to create. But with rapid prototyping and digital fabrication, every created object exists digitally and can be re-fabricated at the touch of a button. And because I was building off of existing models and that the hours of labor were more incremental, each “version” did not feel like something that I had sunk hours into. This knowledge allowed me to play and test each prototype without fear of setting my work back should something go wrong. I could give my performer one of my prototypes and if it was broken or damaged in rehearsal, it would not affect my timeline too greatly. In fact, seeing a prototype break is great feedback for weak points and material suitability.

I have often sat in the audience watching a costume I have made be handled on stage and cringed at how roughly it was being used. However, with the “value” removed from the prototype, I almost wish for the performer to be as rough as possible so that I understand the capabilities of the piece better. In this process, the idea is the commodity, and the prototype is just an avatar for it.

Digital fabrication allowed me to swap pieces in and out of my prototypes. When I was testing out the V-joints for the wings, I tried two different iterations before arriving at the final version. I did not have to re-print the bones themselves to do this process. I was able to focus on one element of the wings and test it in isolation. I suspected that early versions of the joints were weak, and I felt empowered to work with them and stress them until they snapped, confirming my suspicion and allowing me to move forward.

It was also incredibly freeing working with a living model or template for the elements of the wings. Other workflows I have used do not provide much ability to refer back to and edit earlier steps in the process. With more traditional garments made from fabric through draping and patterning techniques, you have a pattern template you can use to cut multiples of a garment, but you still need to perform the labor of marking and cutting out the fabric and assembling it. The paper pattern can be altered with relative ease, but if the edits depart too dramatically from the original you will likely need to re-cut the fabric. When I have used a mold to cast a piece, I am able to quickly replicate the original sculpt, but if you decide later you need to alter the sculpt itself then you need to go all the way back to the sculpting steps of the process, potentially re-doing that step as well if your sculpt didn't survive extraction from the mold. Compare this to working from a digital model where the ability to edit the model is almost limitless and the effort it takes to fabricate after the edits have been applied is incredibly low. There is less of a sense of punishment for needing to make alterations and more of a reward for moving closer to the ideal iteration of your piece.

Which brings me back to the product development methodology used throughout manufacturing industries. For those companies, it is imperative that they create a quality product that has been thoroughly tested and debugged so that the product functions at the highest quality. In theater we have the same goals of high-quality product but are not always given the time to do so due to labor availability and timelines. With rapid prototyping, we can iterate and zero in on that ideal version of our product and confirm its durability and quality through tests without sacrificing hours of fabrication.

EXPANDING MY CONTEXT FOR DEVELOPMENT

Something that I did not anticipate when starting out this process is how the way I approach problems has started to change. Because I have a new set of tools at my disposal, I see more opportunities to use them. This goes beyond just "making something digitally." The digital can be integrated into more physical practices, at various stages, and to a varying extent depending on the process.

On a separate project outside the scope of this thesis, I needed to create a pair of large shoes in clay to cast in plaster. The shoes were exaggerated in size and would likely need 25 lbs. of clay to sculpt. I also had to make two of them, symmetrical just like real shoes are. It occurred to me that I could model a base for the shoes in Fusion

360 and use a slicing software to turn them into a cardboard base that I could sculpt on. I decided to test this idea out, and within a couple hours had a model, a sliced 2D template for a laser cutter to read, and a collection of sliced cardboard pieces assembled into a pair of shoes.

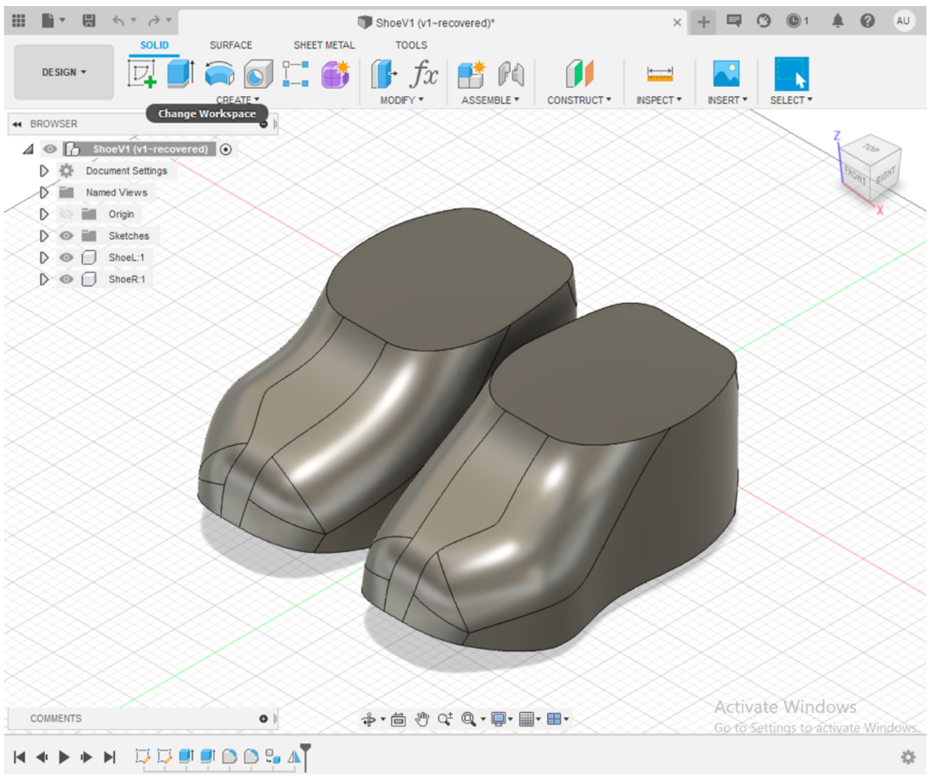


Illustration 58: The shoe model in Fusion 360.

Illustration 59: The shoe model translated into 2D planes, cut in cardboard, and assembled into 3D objects.

Not only was the labor of sculpting two matching shoes at the appropriate scale taken out of the process, but I also saved pounds of clay because the cardboard created an armature to apply clay to.

Illustration 60: A layer of clay was applied to the cardboard base and finer surface details were added to the smoothed surface.

While this was not a project in the scope of my thesis, I felt that this illustrated how this digital fabrication mindset had expanded beyond this project. Even in a context where I was not planning to use digital fabrication tools, I found use for them. The majority of the process was physical and intuitive, but I was able to speed up the step of establishing the right size for the shoe and matching the two shoes to each other. I expect this to become one of many examples of using digital fabrication tools to complement and facilitate the creation of costumes.

The Learning Curve

As with anything, there is a price to be able to access these tools of digital fabrication. In Chapter 2, I looked at the various tools of digital fabrication and their cost and general accessibility to the maker. Having access to these tools is one barrier to entry into the world of digital fabrication. The other barrier is the learning curve.

While the machines themselves are relatively user-friendly and accessible to the casual user, my experience was that the software of digital fabrication can be difficult to master without guidance. When I started learning Fusion 360, I had never interacted with any kind of 3D modeling program, and the controls were very counterintuitive to me - some even to this day. Just learning the basics was difficult and at times frustrating. Once I felt comfortable with the basics, I still had to adjust the way I conceived of building objects in the digital environment and what the best workflows are to achieve those goals. This was an even greater challenge than mastering the basic commands of the program, and I still have a great deal to learn before I could call myself fluent in the program.

I was very fortunate to have J.E. Johnson as a teacher to guide me through the initial months of working with Fusion 360. I found as I learned the program, I performed best when I was able to work on my model in Fusion and ask questions directly as I encountered problems in the process. When I worked on my own, if I encountered a problem, I had to search for answers to it on forums and in instructional videos. This process sometimes meant searching for hours with no guarantee I would find a solution to my specific problem. Some people are well-suited to this kind of problem-solving. But, if I am being honest, I am not one of them. I found that process difficult to work through, whereas I thrived while being able to work independently until I had a question that an expert could answer immediately.

Not everyone has this kind of access to a teacher, and not everyone has the time to educate themselves through the long process of mastering a program. Everyone learns differently and comes into the process with different background knowledge, so a variety of methods of learning can work for a given individual. For people wanting to learn a 3D modeling software, I would highly recommend online resources like LinkedIn Learning (previously Lynda.com), the Autodesk user forums, and Youtube.com as sources for tutorials for guided study. There is a tutorial for almost any function you can imagine online, with the main access barrier being the time to locate them. The other caveat to consider is that there is a certain threshold of knowledge that you have to reach in order for these tools to be useful. Cutting simple shapes on the laser cutter with Adobe Illustrator-generated files is a fairly accessible task but developing workflows in Fusion 360 to be able to iterate and create shapes like the bones is more complicated and takes more time to learn.

This of course is the experience of one person. However, I would consider myself a good proxy for the typical costume artisan who has never worked with 3D modeling software and who did not come to it with a natural aptitude. My main experience with digital tools before Fusion 360 was 2D rendering programs like Adobe Photoshop and Procreate, skills that I found did not translate very well into the 3D world. I was accustomed to certain functions working a certain way and had to unlearn some of those instincts. In spite of the struggle, I did eventually find my footing. Once I cleared the initial obstacles of understanding the basics of my chosen software, I could feel myself starting to think about problems differently. Now I would consider myself a case study for what is possible when given time to really immerse oneself in a new digital language, and how far it is possible to go from such humble beginnings.

THE MARRIAGE OF DIGITAL AND HANDMADE

It is also worth noting that while I moved through this digital and technology-based process, the elements of the handmade were still present. The wings were created through the cooperation of digital and analog processes, and there were some elements of the process that digital just does not serve in the same way.

The wing bones and feathers were fabricated digitally, but their assembly and surface finishes were done completely by hand. Even if I had had access to the types of 3D printers that can print color objects, I still would have chosen to paint them by hand. The hand painted finishing allowed me to really capture and emphasize the contours of the bones with a nuance that digital struggles to replicate. It took relatively little time, and when looking at the finished bones, it is difficult to tell that they were 3D printed at all!

I also assembled the wings by hand. Because I was using different types of materials, they had to be assembled in steps separate from their fabrication. Laying the feathers out was probably the most intuitive step in the process, though even this could be guided by creating a 2D printable template for the feathers and laying the bone and feathers on top of it.

One might also notice that this thesis revolves around the fabrication of the owl wings but mentions the fabrication of the head only in passing. That is because when I first was planning the full-picture construction of Lechuza, I anticipated that the head would have to be incredibly durable, yet also lightweight. The scale of the head did not lend itself to 3D printing - at least the 3D printing I had access to - because it would have had to be printed in pieces and glued together, something that felt risky for the structural core of the head. I had to assume that her body could and would be dropped on the ground, and that it would have to be able to withstand such stress without shattering. It is certainly possible for 3D printed objects to withstand a lot of stress, but that is directly related to the thickness and amount of infill of the object. The thicker and denser the print, the heavier it would become, and I was not convinced that I would be able to achieve a head lightweight enough to be comfortable to wear that would also be suitably durable through digital fabrication. So, in this situation of needing to balance durable flexibility and a lightweight material, I turned to the more traditional medium of paper-mâché.

However, just because every problem cannot be solved digitally, does not mean that it cannot integrate with or improve traditional practices. The shoe example from the previous section is just one instance of how digital and traditional practices can complement each other and use the strengths of both to improve workflow. Perhaps 3D printing the head and body structure could have worked if I had access to more or larger 3D printers and a little more time to do strength tests on such large prints. I could have also experimented with printing the head at scale, and then casting it in another more lightweight and durable material.

FINAL CONCLUSIONS

Reflecting back on the questions that guided my initial investigation into digital fabrication and its impact on costume development, I am reminded of how far I have come in expanding my skills in this area and how much my own process has been impacted. I began this research process suspecting that the revolutionary impact of digital fabrication, the maker movement, and rapid prototyping could have a similar impact in the field of costume making for theater. Now, I am absolutely convinced that these tools and processes can and should absolutely be integrated into costume shops around the country and the world.

I now look at potential projects or designs and automatically identify elements that would be well-served by digital fabrication processes. My ability to model in Fusion 360 has developed not to a point of mastery but far enough along that I am able to problem-solve most issues I come across, and I have a vocabulary that lets me search for answers to issues online with relative ease.

Having these basic tools at my disposal and having worked my way through a project with rapid prototyping, I am confident that I can and will use these workflows in my projects moving forward. Utilizing digital fabrication in my work has elevated its quality and professional polish and allowed me to refine costume pieces in ways that I have not been able to before.

Illustration 61: The completed costume with the wings bent, demonstrating the range of motion of the wings.

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